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1987–1988

REPORT

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SPACE SCIENCE AND APPLICATIONS

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SCIENCE, SPACE, AND TECHNOLOGY
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ONE HUNDRED FIRST CONGRESS
FIRST SESSION
Serial B

MAY 1989

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I. Pursuant to House Report 99-829 to accompany H.R. 5495, the Fiscal Year 1987 NASA Authorization Bill for the Committee on Science and Technology requested that NASA submit the following reports, summaries, plans, to the Congress or Committee:

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II. Pursuant to House Report 100-204 to accompany H.R. 2782, the NASA Authorization Bill for Fiscal Year 1988, the Committee on Science, Space, and Technology requested that NASA submit the following reports, summaries, plans, to the Congress or Committee:

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NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: C:AP:brb

APR 17 1987

Honorable Bill Nelson
Chairman
Subcommittee on Space Science
and Applications
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed per House Report 99-829 to the NASA Authorization Bill of 1987 is a report on NASA's Space System Development Agreement (SSDA) deferred payment option. The committee's recommendation that a "less subjective and restrictive approach" to accomplishing the goal of encouraging commercial profit-making space endeavors is also addressed.

Sincerely,

John F. Murphy
Assistant Administrator
for Legislative Affairs

Enclosure

cc: Honorable Robert S. Walker

Office of Commercial Programs

Policy on Space Systems Development Agreements

The House Authorization Report 99-829 requests that NASA review the Space System Development Agreement (SSDA) deferred payment option and make a recommendation to the Committee on a "less subjective and restrictive approach" to accomplishing the goal of encouraging commercial profit-making space endeavors.

The only restrictive aspect of the SSDA policy is that the flexible payment schedule is available only to the first to market of a particular industry. This payment aspect empowers the SSDA to be a useful tool and catalyst. The flexible payment provision of the SSDA can provide an effective incentive to entrepreneurial investment in infant industries. NASA has chosen this restriction to reward aggressive entrepreneurs who make the extra investment of resources and time to be the first venture to market.

The Committee expressed concern over how NASA intends to determine who is first to market with a particular idea. Specifically, they are concerned that the deferred payment option would be given to the first person to approach NASA, regardless of whether or not he in fact was the first person with a particular idea.

In responding to these concerns directly, a point of clarification is necessary. NASA does not see its role as one of determining who is first with an idea. The objective of the SSDA provision is to determine who has the greatest ability to succeed with an idea or a project and be the "first to market." NASA uses, as an indicator for this purpose, the venture's ability to develop a proposal and approach the agency regarding necessary flight testing or placement.

A great idea is useless if it cannot be brought forward and aggressively marketed. Although there are a great many factors that contribute to the success or failure of a potential product, the ability to identify a need, design a product, and take the necessary steps to bring it to market are certainly some of the most critical. The congressional and presidential mandates regarding the commercial development of space is to increase private sector commitment and investment in commercial space activities. For this reason, the SSDA is specifically not based on who thought of it first. The SSDA seeks to reward those ventures having the combination of vision, aggressiveness, and organization to be the "first to market."

In addition, the current number of organizations capable of commercial development work in space is extremely limited, and information within the space community spreads quickly. It is fairly simple to determine whether or not a particular idea is being developed elsewhere.

The principal objective of the SSDA is to incentivize entrepreneurs to develop concepts for potential space commerce, take healthy and reasonable risks in an aggressive fashion, and reward these same entrepreneurs with some flexibility regarding upfront capital requirements.

The notion of rewarding the first to market is not unique to NASA. The concept of patent protection is modeled on the same principle of offering limited protection to a new idea or product for a limited amount of time.

The Committee has requested that NASA consider an alternative to the current SSDA policy. The alternative to the current policy is to offer the SSDA to subsequent proposers. This, however, defeats the very purpose of the agreement. The logic behind offering the SSDA to only the first proposer is very simple. The first venture to market lays the groundwork of an industry. They pay more than anyone else in a particular industry to identify a need, define a market, identify consumers, develop a product, and create a marketing campaign. The second to market already has a paved road and a ready-made product.

Requirements for the company ~~requesting~~ the SSDA option are minimal: the presentation of a business plan showing some reasonable ability to succeed financially and ability to generate sufficient revenues to afford repayment to

NASA. NASA does not attempt to evaluate the subjective value or worth of an enterprise. NASA only evaluates the credibility of its organizational/financial planning and backing.

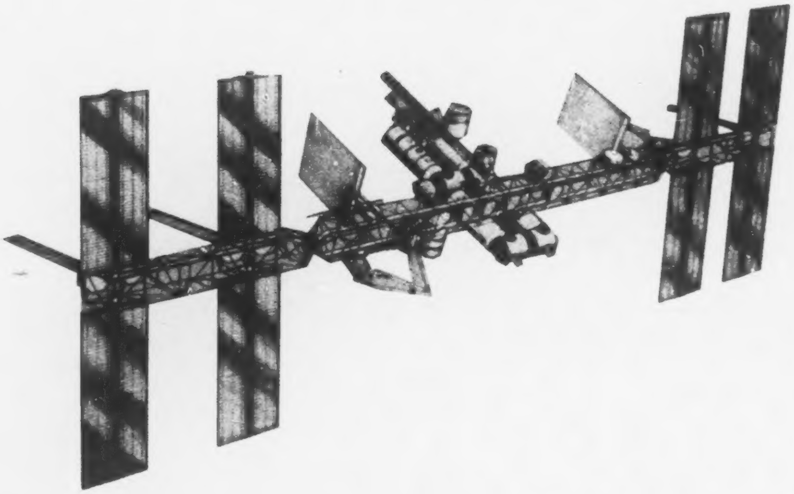
The Committee's suggestion regarding budgeting the number of SSDA's that could be flown in a particular year as a planning mechanism is well taken and will be seriously considered as flight status resumes to some regularity.

NASA
National Aeronautics and
Space Administration

SPACE STATION DEVELOPMENT PLAN

Submitted to the

Committee on Science, Space and Technology
U.S. House of Representatives



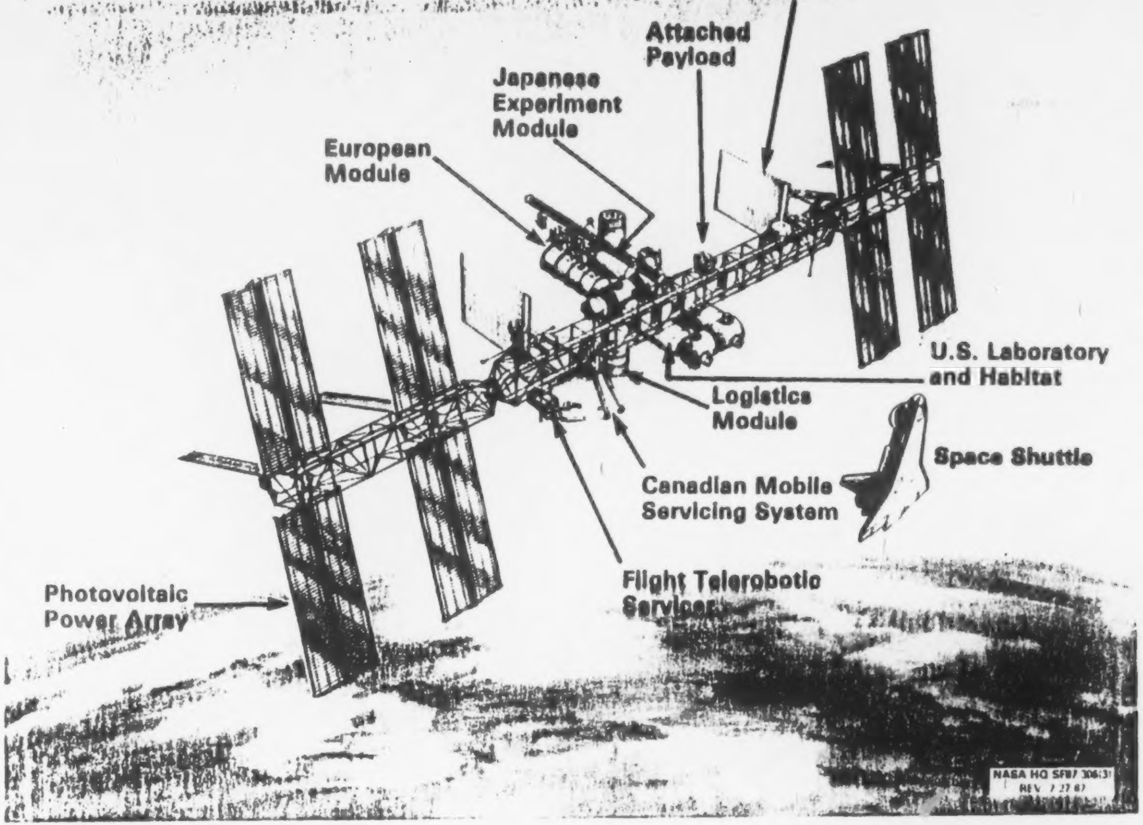
NOVEMBER 1987

PREFACE

The Space Station Development Plan is submitted in response to a request by the Committee on Science and Technology, U.S. House of Representatives, in Report No. 99-829. This report, dated September 16, 1986, dealt with FY 1987 NASA authorization (H.R. 5495). The Space Station Development Plan is submitted in conjunction with reports on Science Operations Management and Operations Cost Management.

This plan is based on Space Station Program internal planning and control documents. Those reference documents specify approved Program requirements and schedules and are under configuration control. This plan, at the time of publication, is consistent with those documents and represents Program planning as of the completion of the definition phase but prior to initiation of development activities. It is consistent in content, schedule, and cost with the program which was endorsed by the Administration in April 1987. During the implementation of Space Station development changes which occur in the Program baseline will be reflected in annual updates to this Plan.

Space Station Manned Base


Radiator
Attached Payload
Japanese Experiment Module
European Module
U.S. Laboratory and Habitat
Logistics Module
Space Shuttle
Canadian Mobile Servicing System
Flight Telerobotic Servicer
Photovoltaic Power Array
NASA HQ SF87-306(3)
REV 7-27-87

SPACE STATION DEVELOPMENT PLAN

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INTRODUCTION

A Laboratory in Space

The United States is building a new national laboratory – the Space Station. As a research facility in space, it will provide opportunities for significant advances in science, technology and commerce. Orbiting the Earth once every 90 minutes, the Station will take advantage of the unique Space environment. The near absence of gravity (microgravity) will enable the U.S. to conduct productive research in life and materials sciences and to conduct scientific observations of the Earth and the stars.

The Space Station, unlike any spacecraft yet developed by the United States, will be permanently manned. Time on orbit will no longer be constrained to a few days. No longer will we visit space, men and women will be living and working in space continuously. Machines, however sophisticated, cannot do what the Space Station crew will do: think and react to the unexpected. Human presence is the key to providing a Station that has creative and dextrous capabilities.

A Stepping Stone in Space

In the future, Americans will again venture beyond the environs of Earth. The objective of the Apollo Program, to explore the moon, was a beginning not an end. Expeditions to Earth's sister planet Mars, or back to the moon, will inevitably take place. When this will occur and who will do it are uncertain as other nations throughout the next century expand their technical capabilities to meet these goals.

Any such missions would utilize a Space Station as a point of departure. But much preparatory work is required if these missions are to be considered in the future. Technologies must be developed, experience in complex space operations must be gained, and knowledge of the effects of extended space flight on humans must be expanded. A Space Station provides the essential facility in which to carry out these tasks. The Space Station represents an investment in these activities but would not be a commitment to a manned mission to Mars or a return to the moon. Such future missions would better be accomplished by first developing the Space Station. It will be our stepping stone in space, if we choose to make it so.

The Space Station Program

This development plan describes the Program that NASA has established to build the Space Station. The Program draws upon the experience of both NASA and industry. It is shaped by the availability of resources, the elements of schedule and the capabilities desired. It is shaped also by NASA's insistence on developing a Space Station that is truly first-rate in capability. The Station must be a research facility capable of supporting a variety of scientific disciplines. It must be flexible yet durable in its capabilities, as the Station will be on orbit for many years. It must be operationally affordable for its success will be measured by its operational use and not its development.

Space Station must be compatible with the Space Shuttle, which will reflect the intention of the United States to remain the leading nation in space as the 20th Century comes to a close.

Program Planning

The Space Station program differs from previous NASA endeavors in a number of significant ways. Program planning has been based on an extended period of detailed definition by NASA with parallel efforts in Canada, Europe, and Japan. The modular Station design, consistent with current launch capabilities, dictates multiple launches and on-orbit assembly. U.S. development and test responsibilities are distributed among five NASA centers to draw on unique skills and resources throughout the agency. The efforts of these centers and their aerospace industry contractors will be integrated by the NASA Headquarters Space Station Program Office (SSPO) in Reston, VA. The SSPO will be assisted by the Program Support Contractor (PSC). The SSPO will also have the responsibility for integrating major international elements into the Program.

The Program differs also in the potential for having private sector participation in space station development and operations. NASA policy welcomes private funding of dedicated Space Station systems and services.

The participation in Space Station development by many NASA programs is another unique aspect of this program. The Space Station will provide a key part of the overall capabilities needed to accomplish civil space objectives. In addition to the participation of the international partners, the NASA Office of Space Flight, Office of Space Operations, Office of Space Science and Applications, Office of Aeronautics and Space Technology, Office of Commercial Programs are providing support to the Office of Space Station that is essential to a successful Program. Cooperative agreements and compatible plans for Station development and operations are key elements of the development strategy.

An unusual but significant aspect of the Space Station is its long operational life. This space-based facility is designed to be permanently inhabited well into the next century. Manned and unmanned elements must be designed to permit changes to avoid obsolescence and to accept efficient on-orbit maintenance and resupply.

Operations capability is an element of Space Station planning. The development of this capability is consistent with hardware and software systems development in all respects: schedule, cost, budget, management, and design compatibility. Operations studies leading to design requirements are being conducted as an integrated part of the development. Engineering and operations schedules are coordinated to ensure the operations facilities are in place and the manpower is trained to meet the hardware processing, launch, and assembly schedules. An operations task force developed a management concept and recommendations for system design and operations which are now being implemented in the Program. The recommendations on how the Program should support users and how user groups might be organized have been studied and reported on by a Science Operations Working Group. Design compatibility will be ensured through operations suitability and supportability assessments. These assessments will review designs and plans to verify that they meet operations requirements and can be supported with available resources. An Operations Cost Management Plan will allow trade-offs between development and operations costs to obtain low life-cycle costs.

At the request of the Administration, the National Research Council (NRC) conducted an independent review of the Space Station Program which considered Program objectives and requirements, potential phasing of capabilities, costs and lower cost alternatives, and Station capabilities and Program schedules. The review was completed in September and the NRC made a number of recommendations. NASA agrees with most of these recommendations and is particularly encouraged by the NRC's endorsement of the Space Station configuration.

Space Station cost estimates have been developed and extensively reviewed. An intensive 21-month Phase B definition produced reliable cost estimates that were reviewed for over a year by NASA, the Administration, and the NRC. The result is a development program that has remarkably well-understood cost parameters. As reported earlier to the Committee on Science, Space, and Technology, the cost estimate for Space Station is $14.6 billion in 1988 dollars.

The Development Plan

This development plan presents the strategy and structure of the Space Station Program Office. It contains a top-level Program description. The Plan begins with a review of Space Station Program Objectives and Requirements.

I. REQUIREMENTS

A. PROGRAM OBJECTIVES AND REQUIREMENTS

Program Objectives

In 1981 NASA Administrator James Beggs stated the widely held belief that the next logical step for the U.S. space program was to build a permanently manned space station. The Space Shuttle had flown, and the establishment of a permanent facility in space to which the orbiters would shuttle was a step the United States would have to take were it to continue to lead in the exploration of space. On January 25, 1984, following several years of requirements studies, in depth reviews, and Presidential briefings, President Reagan issued a mandate in his annual State of the Union address to the nation: "We can follow our dreams to distant stars, living and working in space for peaceful, economic, and scientific gain. Tonight, I am directing NASA to develop a permanently manned space station and to do it within a decade."

The Space Station will add new momentum to the civil space program and is essential to realizing the national goal of restoring U.S. leadership in space. The objectives of the Program are:

(1) To establish a permanently manned research facility in low-Earth orbit by the mid-1990s with the capability to evolve to meet future needs;

(2) To enhance and evolve mankind's ability to live and work safely in space;

(3) To stimulate technologies of national importance (especially automation and robotics) by using them to provide Space Station Program capabilities;

(4) To provide cost-effective operation and utilization of continually improving facilities for scientific, technological, and operational activities enabled or enhanced by the presence of man in space;

(5) To promote substantial international cooperative participation in space;

(6) To create and expand opportunities for private-sector activity in space;

(7) To provide for the evolution of the Space Station Program to meet future needs and challenges; and

(8) To provide unmanned platforms for long duration scientific and operational observations.

The combination of manned, unmanned, and automated systems will establish a broad spectrum of capabilities responsive to both currently identified and evolutionary needs of space science, technology, and commerce.

Program Requirements

The Space Station Program will include a permanently manned Space Station, unmanned platforms, and the associated ground-based infrastructure. The major physical elements of the configuration provided by the United States will include pressurized habitation and laboratory modules with a shirt-sleeve environment for crew habitation and for conducting experiments under microgravity conditions, resource nodes for command and control, airlocks for Extravehicular Activity (EVA), accommodations for attached payloads, the Flight Telerobotic Servicer (FTS), a polar orbiting platform, logistics elements, and EVA capability.

The configuration is expected to include elements provided by the Program's international partners. These elements are the Japanese Experiment Module (JEM) which includes a pressurized laboratory, an exposed facility for payloads, and a logistics module; the Canadian Mobile Servicing System (MSS); and the European Space Agency (ESA) pressurized laboratory, polar orbiting platform, and Man-Tended Free Flyer (MTFF).

The Space Station will be able to support a crew of eight and provide a total average power level of not less than 75 kW using photovoltaic arrays.

The ground-based infrastructure needed for Space Station operational capability will include facilities for mission control, logistics support, launch processing, training, testing, and user operations.

The on-orbit capability will increase during the assembly sequence leading to complete deployment and operation of the station. Growth of on-orbit capability will have the following characteristics:

(1) The FTS will be available early in the Program so as to support assembly and maintenance tasks and payload installation.

(2) Attached payloads will be added before the manned modules are launched.

(3) Man-Tended Capability (MTC) will be achieved with the addition of the laboratory module. MTC will provide for support of selected payloads and experiments prior to the time at which a crew is continuously present.

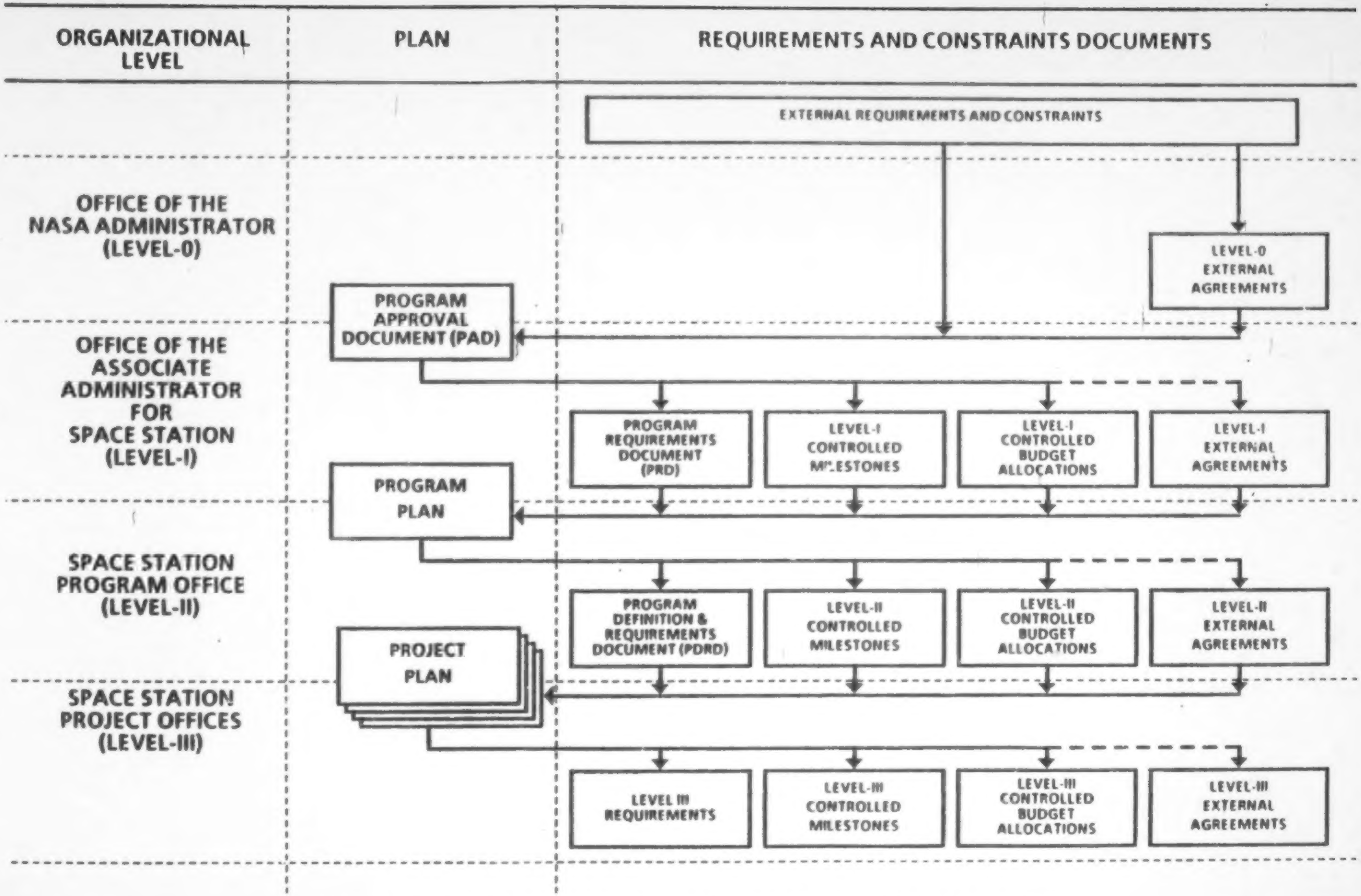
(4) The flight sequence will include the launch of both U.S. and ESA polar platforms (each with integrated payloads) into high-inclination polar orbits to provide capability for scientific and operational Earth observations.

(5) Permanently Manned Capability (PMC) will be achieved with the inclusion of the U.S. habitation module, safe haven provisions, and Space Station-based EVA capability. At this point the Space Station will be capable of continuously supporting a crew of up to eight people.

Space Station elements will be delivered to orbit by the National Space Transportation System (NSTS), except for ESA delivery to orbit of the ESA polar platform and MTFF. Alternative transportation modes that could increase Program margins and reduce requirements placed on the NSTS are under study. Five shuttle flights per year for sustained operations will be the Program baseline. The Space Station Program will require launch support from both the Eastern Test Range and Western Test Range.

Evolution is the process of increasing the on-orbit capability of the Space Station to meet evolving requirements. The Space Station design will facilitate future evolution by including provisions for adding payloads, increasing resources such as power, new functional capabilities such as accommodations for an Orbital Maneuvering Vehicle (OMV) or a servicing facility, a co-orbiting platform, and the incorporation of new technologies.

Top-level Program requirements are specified in the Program Requirements Document (PRD). The design requirements for Space Station development are specified in the Program Definition and Requirements Document (PDRD). The hierarchy of program documentation is shown in Figure I-1. Element and system performance capabilities are described in Appendix A, System Description.


ORGANIZATIONAL LEVEL
PLAN
REQUIREMENTS AND CONSTRAINTS DOCUMENTS
EXTERNAL REQUIREMENTS AND CONSTRAINTS
OFFICE OF THE NASA ADMINISTRATOR (LEVEL-0)
LEVEL-0 EXTERNAL AGREEMENTS
OFFICE OF THE ASSOCIATE ADMINISTRATOR FOR SPACE STATION (LEVEL-I)
PROGRAM APPROVAL DOCUMENT (PAD)
PROGRAM REQUIREMENTS DOCUMENT (PRD)
LEVEL-I CONTROLLED MILESTONES
LEVEL-I CONTROLLED BUDGET ALLOCATIONS
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PROJECT PLAN
LEVEL III REQUIREMENTS
LEVEL-III CONTROLLED MILESTONES
LEVEL-III CONTROLLED BUDGET ALLOCATIONS
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FIGURE I-1. SPACE STATION PROGRAM DOCUMENTATION FRAMEWORK

B. UTILIZATION

User Requirements

Utilization of the Space Station has been the focus of Program conceptual and definition studies. Two years before the start of Phase B definition studies, prospective users were asked to propose potential payloads for the Space Station. Workshops were held to review these prospective payloads. These payload descriptions were compiled into a Mission Requirements Data Base (MRDB) containing over 300 individual potential missions or payloads.

The MRDB is a computerized data base that can support a variety of Space Station design accommodation studies. The MRDB will be updated throughout the life of the Space Station to assess the adequacy of payload accommodations and to evaluate the need for evolution of Space Station accommodations. An analysis of the early MRDB provided the basis for the initial set of user requirements placed on the Program.

Payloads for the initial phase of the Space Station have been recently identified by the Office of Space Science and Applications, Office of Aeronautics and Space Technology, and Office of Commercial Programs. These candidate payloads will be maintained as a near-term mission subset. Additional subsets containing candidate payloads to be accommodated in later Program phases will also be developed. The subsets will be used to conduct detailed accommodations studies for the early phase of the Space Station development program.

User Accommodations

Space Station user accommodations were initially identified and integrated into Space Station systems and configurations designs based on extensive analyses of the MRDB. These assessments were aided by extensive interaction with users and user sponsors in the Space Station User Requirements Working Group, International Utilization Coordination Working Group, the Task Force on Scientific Uses of the Space Station, the Commercial Advocacy Group, the Technology Advocacy Group, the Space Station Mission Integration Panel, and other user working groups and technical systems panels.

To confirm the adequacy of user accommodations and to assess the Program's ability to support new payload requirements will require detailed accommodations studies during the development phase. The studies will assess candidate sets of payloads and develop potential manifests. These activities will include both U.S. and international payloads. Payload viewing and pointing angles, power availability, data and command system capability, disturbance environment, optimum locations for payloads sensitive to contamination and electromagnetic fields, crew operations support, remote manipulator support, and resupply logistics are some of the accommodations that must be addressed.

Extensive accommodation analyses have been conducted for payloads in microgravity materials and life sciences, Earth observations, technology, astrophysics, plasma physics, induced environment, and planetary studies. Pointing payloads such as the Tropical Rainfall Measurement Mission and the Solar-Terrestrial Observatory solar observing instruments have played an important role in determining the level of Space Station support required for payload pointing.

Materials-processing equipment such as crystal growth facilities (e.g., for protein and gallium arsenide crystals), a containerless materials processing facility, and fluids processing facility (e. g., for electrophoresis) have been drivers in determining the microgravity requirements for the Space Station and in turn the location of the modules with respect to the truss. Life science payloads, biomedical and biological, also have microgravity requirements.

Crew intensive experiments are primarily those inside the laboratory in particular the life science biomedical and biological payloads. Depending on the degree of automation, some materials-processing experiments will also require substantial crew support. The majority of the external payloads are automated or can be operated extensively from the ground. Exceptions are instruments or payloads which require extensive crew interaction to provide the desired data.

Accommodation studies of space assembled payloads such as the Large Deployable Reflector, geosynchronously deployed antennas, and assembly support manned lunar and Mars missions are ongoing. Additional facilities such as a large positioning mechanism or crane may eventually be needed to support assembly activities in a future growth phase after the current program.

In addition to these primary accommodation assessment activities, developments in A&R will be emphasized to ensure that the Space Station takes advantage of capabilities which can greatly increase payload productivity and utilization with minimal cost increases.

The Task Force on Scientific Uses of Space Station of the NASA Advisory Council served to bridge the NASA scientific user community and the Space Station. NASA has begun to establish a follow-on group to continue this service. Selection of a chairman and members is under way.

The NASA Headquarters organizations representing the science, technology, and commercial users have recently submitted an updated assessment of the payloads supported by the user community for manifesting during the assembly of the Space Station. These payloads are typical of what can be expected for the Space Station.

For example, before the Man-Tended Capability (MTC) is achieved, the baseline assembly sequence will provide the capability to install payloads on the transverse boom which would provide the following: (1) measure and assess the Space Station plasma environment to improve our understanding of the physical interactions between large structures and space plasmas and to gain a better understanding of the physics of space plasmas (e.g., Space Station Plasma/ Environment Monitoring System); (2) collect meteoroid and cometary dust for analyses related to solar system evolution, planetary formation, and the development of life in a planetary system (e.g., Cosmic Dust Collection Experiment); (3) study solar phenomena (near the peak of the solar cycle) and the interaction of the solar wind and Earth atmospheric and magnetospheric processes (e.g., Solar-Terrestrial Observatory solar instruments); (4) evaluate the effectiveness of using laser beams as data communication links between satellites and spacecraft (e.g., Laser Communications Engineering Test); and (5) study the effectiveness of different types of materials and coatings in resisting oxygen erosion, solar ultra-violet degradation, and orbital debris effects (e.g., Spacecraft Materials and Coatings). Some sensors such as accelerometers, strain gauges, and contamination and plasma monitors may be integrated into the truss structure as it is assembled to characterize the Station.

Subsequent flights will deliver the U.S. laboratory and additional payloads and payload support equipment for the laboratory and a node. Payloads similar to the following will be included: Commercial Protein Crystal Growth Facility, Isoelectric Focusing Experiment, Two-

Phase Fluid Behavior and Management Experiment, Biomedical Research Project Experiment (may be located in Node 4), Very High Speed Integrated Circuit Fault Tolerant Processor, and Manned Observations Techniques. Other payloads such as Quantized Vortex Structure, Transient Upset Phenomena in Very Large Scale Integrated Circuits, Modular Containerless Processing, Organic Crystal System, and Life Science Biomedical and Biological Research Project payloads will be delivered by later flights.

The Utilization and Operations Board (UOB), a part of the Space Station Control Board structure, will be the primary means to obtain approval for user accommodation changes, additions, and reductions. The UOB will sponsor several important working groups including the Pressurized Payload Accommodations Working Group and the External Payloads Accommodations Working Group. These and other working groups will address user accommodation concerns, review proposed design changes, and preview and status the results of major Program design review activities. Section IIB describes the structure of Program boards and panels.

C. OPERATIONS INTEGRATION

As noted in the introduction, the Space Station Program draws heavily upon the resources and capabilities of other NASA Offices for its support. The Office of Space Flight is necessarily relied upon to provide the NSTS for transportation and to support on-orbit assembly and integrated operations. It is the intent of the Space Station Program to develop a manned base and a series of platforms that satisfy user requirements within the integrated support capabilities of the NSTS, TDRS, OMV, and Space Station Programs. To this end joint working groups and agreements will be established to coordinate and assess the needs of the Space Station Program. The goal of these working groups will be to blend the new Space Station capabilities with the existing capabilities and capacities of the manned programs.

The integrated approach will also benefit user integration by utilizing the complete on-orbit support provided by the combined capabilities of the Office of Space Flight, Office of Space Operations, and Office of Space Science. The various Space Station management boards will include membership from the other NASA offices to ensure compatible and integrated concepts and implementation through their participation in the decision making process.

The Space Station Program is responsible for developing a Space Station that can be implemented, assembled, and operated with the coordinated capabilities of all manned Program elements. Manned base assembly operations will be a joint OSF and OSS activity with OSF performing the on-orbit assembly tasks. OSS will provide compatible flight hardware and support operations to this activity.

The Space Station Program must also blend easily with the unmanned programs of NASA, specifically the Space Science program and the data tracking activities. OSO and OSSA will provide essential operations support.

D. INTERNATIONAL PARTICIPATION

President Reagan's 1984 State of the Union message included a call to friends and allies of the United States to participate in the Space Station Program. He stated, "NASA will invite other countries to participate so we can strengthen peace, build prosperity and expand freedom for all who share our goals."

Even prior to this call, NASA planning criteria included the potential for significant international participation in the Program. It was understood that such participation, in addition to continuing the NASA tradition of international cooperation in space activities, had significant potential for enhancing Space Station capabilities, supporting U.S. foreign policy objectives, and sharing the risks and operational costs of the endeavor. Through cooperation enhanced overall capability can be achieved with minimal shared investment in development and operation.

In 1982, NASA initiated studies of Space Station needs, attributes, and architectural options. In addition, potential partners in Europe, Canada, and Japan conducted parallel studies. All potential partners responded enthusiastically, and the results of the parallel studies were shared in the spring of 1983 and factored into preparations for the definition phase. The potential partners also participated in a concept development group formed by NASA in 1983. They studied selected tasks and the results were shared in workshops. In order to further coordinate predefinition activities and share status information, international meetings were held in Washington, D.C., in 1984 at which preliminary guidelines for international cooperation were presented by NASA and discussed with officials from Canada, ESA, and Japan.

Agreements to set the framework for cooperation in the definition phase were signed in the Spring of 1985 with Canada, ESA, and Japan. These agreements included preliminary design and definition studies and established a process to identify elements of the Space Station that could be developed by the partners. Based on the process established by the Phase B agreements and preliminary results of the definition studies, Program level agreements were reached in 1986 with all three partners. These agreements identified hardware elements which each partner would study for development, subject to further agreements on the detailed design, development, and operations and utilization phases. These agreements will provide bilateral management mechanisms for the development phase set forth in Section IIB, Management Approach. The international hardware elements are described in Appendix A, System Description.

The approach for international cooperation in the Space Station Program is based upon successful practices followed by NASA in more than 25 years of cooperative international activities. Because of the maturity of foreign aerospace capabilities and because any Space Station cooperation would extend for a considerable length of time, NASA has understood that any such cooperation would be on the basis of partnership. While NASA retains overall Program direction, the international participants will have a major role in Station development and operations. The long term nature of the Space Station Program dictates additional considerations; therefore, the partners are developing long term utilization plans and will be responsible for selecting and prioritizing their own users. They will remain responsible for the elements they provide and will maintain and support the ongoing operations of their respective elements. Special care will be taken to ensure that no unwarranted transfer of U.S. technology occurs. International partners will provide personnel to serve as crewmembers and will share the operations costs of the Space Station. Multilateral management mechanisms will be established to determine strategic and resource allocations. Details of the international roles and responsibilities are the subject of current negotiations. Other aspects of international participation are described in relevant sections as appropriate.

Currently studies are being conducted to determine the feasibility and salient features of international partners (ESA and Japan) providing their logistics transportation via their launch vehicles.

II. IMPLEMENTATION

A. DEVELOPMENT STRATEGY

Introduction

The purpose of the Space Station Program is to provide space-flight users with operational capability consisting of Earth-orbiting manned and unmanned facilities and the requisite ground operation and support systems.

The Space Station configuration described in this document will provide the United States and its potential international partners with a facility capable of supporting a permanent, manned presence that is both affordable and attractive to a large group of users. The current NASA plan will result in a manned base that can accommodate international elements, unmanned orbiting platforms, and the development of an operational capability. Inherent in the current revised baseline design is the technical capability for growth of the Station, concurrent with its initial operations, into a configuration with greatly increased capacity to support payloads and provide services to the users.

The Program guidelines encourage U.S. industry investment in the development and operation of the Station. These guidelines are directed to U.S. commercial enterprises which seek to develop with private sector funds Space Station systems and services. The guidelines provide for appropriate incentives as well as protection for commercial proprietary rights. Participating commercial enterprises would retain responsibility for sustaining engineering, operational support, management, financing, and spare parts for their products or services.

Program Definition (Phase B)

A major element of NASA's development strategy for the Space Station Program has been to conduct a comprehensive Program definition phase which drew heavily on past experience in NASA program management and the technical expertise that exists in both the NASA field centers and U.S. industry. The Program actively solicited advice from outside communities on key matters such as user requirements, configuration, program management, evolution, technical risk, safety, commercial and international participation, and projected program costs.

Throughout Phase B, completed in January 1987, NASA involved the user community in all major aspects of the planning process. Mission requirements were solicited from federal, scientific, international, and commercial sources and reviewed by various advisory groups. The user community continues to have representation at all levels of the Program. NASA is sensitive to the need to keep payload procedures simple and timelines short.

NASA believes that life-cycle costs, particularly development, transportation, and operations costs, must be kept to the minimum consistent with crew safety and mission requirements. In the Phase C/D RFPs, NASA has requested that proposals include cost saving approaches which NASA plans to consider in the RFP evaluation process.

A major Program objective is to stimulate technologies of national importance, such as A&R, by using them to provide Space Station capabilities. The FTS is the centerpiece of the Space Station Program's A&R activity. The programs A&R strategy is designed to:

- Apply selected elements of state-of-the-art A&R technologies to increase crew safety, Station productivity, and cost-effectiveness;

- Provide, in the Station baseline, design features for the future application of more advanced A&R during Station evolution; and

- Support the development of advanced A&R technologies that improve Station evolutionary capabilities and transfer appropriate elements of these technologies to terrestrial applications.

The Advanced Technology Advisory Committee reports semiannually to the Congress on NASA progress in incorporating A&R into the Program. NASA has requested in the Phase C/D Requests for Proposals (RFP)s that offerors include in their proposals A&R applications for the Space Station and how they would tailor their design to allow evolution to an expanded A&R capability.

During Phase B the Advanced Development Program funded promising areas of technology applicable to the Space Station. The following discusses the four categories of the Space Station Advanced Development Program:

- Flight experiments of technologies that have demonstrated feasibility during ground test confirm performance in the Space Station environment. A typical example is the heat-pipe experiment that is scheduled to fly on the NSTS.

- The construction and use of ground system test facilities called "test beds" verify the end-to-end performance of distributed systems. A typical example is the Data Management Test Bed at Johnson Space Center (JSC).

- Prototype technology accelerates development of projects that have shown promising breadboard performance but must be successfully tested in a realistic Space Station environment of a flight-like configuration before the design may be applied to the Space Station. A typical example is the two-phase thermal loop.

- Focused technology includes promising, ongoing technology projects that have not progressed to the degree of development where application can be planned but show high enough Space Station application benefit that their development should be accelerated. For example, development of the technology of solar dynamic electric power generation is being given a high priority.

The Phase C/D contractors will be authorized to use the NASA advanced development test beds in accordance with their development contracts. The NASA strategy is to assist the hardware contractors in evaluating technical approaches at minimal dollar and schedule cost. Test beds are located at all Space Station hardware development centers.

Design and Development Phase (Phase C/D)

The U.S. Space Station elements will be developed by four NASA field centers with overall Program direction by the Program Office (Level II) in the Washington, D.C. area. Development will be supported by competitively selected contractor teams. A more detailed description of field center development assignments and management responsibilities is contained in Section IIB, Management Approach.

NASA's development strategy for the Space Station deliberately precluded utilization of a single prime contractor. For a program of such extended duration as the Station, dependency upon one company would not be in the best interest of the government. Moreover, the "work package" approach better utilizes NASA expertise at the field centers and fosters greater competition among U.S. industry. An essential component of this strategy is that NASA would be responsible for the overall System Engineering and Integration (SE&I) of the Program. The work packages have to be tied together. NASA, rather than a prime contractor, will perform this essential task. To assist NASA in this function, the Space Station Program Office has procured the services of a Program Support Contractor (PSC). This contractor, Grumman Aerospace Corp., was competitively selected, for work package assignments were excluded from the Program Support Contract SE&I is discussed later in this report.

In late 1986 and early 1987, prior to the release of the major hardware RFPs, NASA reviewed the Space Station configuration that emerged and the projected Program costs and capabilities. The revised baseline configuration will provide a permanently manned system with pressurized laboratory and living space, accommodations for attached payloads, a polar-orbiting platform, accommodations for potential international elements, and for growth.

Throughout the development process the design will mature to meet Program requirements. The change control process is discussed in Section II B.

Assembly of the Space Station will be done on orbit. Assembly is planned to be started in the spring of 1994 and is currently scheduled to be completed by the end of 1996. The U.S. polar platform is now scheduled for launch in 1995. Future decisions on the next phases will take advantage of accommodations for the evolutionary growth of Station capabilities.

One of the primary objectives of Phase B activities was the retention of evolutionary growth capability for the Space Station. During Phase C/D new requirements associated with evolution of the Program content and capabilities may emerge. At any given point in time, there will be a carefully defined demarcation between those parts of the Program which have been baselined and properly approved for detailed design, development and certification and those which are still under study.

Phase C/D contains an initial period of approximately four months for refinement of the design requirements. In this period, all requirements related to the approved Program content are analyzed by the selected contractors and reviewed with NASA management and support personnel. This process will create a potential for change to the baseline but is necessary to assure that the requirements are consistent and are understood by the selected contractors. This portion of the activity will terminate in a formal Program Requirements Review (PRR) 90 days after Contract Start Date (CSD) and will result in the start of detailed design.

The PRR evaluates the status of the Program and defines actions to be accomplished in order to proceed with the detailed design and release of fabrication requirements. The PRR considers Program content, milestones, schedules, and plans; the Work Breakdown Structure (WBS); and unique requirements of potential international projects including technical ground rules, waivers, and agreements with other NASA organizations.

The preliminary design period will respond to validated requirements with layouts of all primary hardware definition of interfaces and detailed fabrication, procurement, test, evaluation, and certification plans and procedures. The Preliminary Design Review (PDR) will be carried out first at the work package level and then at the program level. PDR activities include review of the system design, engineering study results, preliminary test requirements, schedules, and other programmatic requirements. As a

result of this review, Contract End Item (CEI) specifications; layout and assembly-level hardware, software and interfaces; and top-level fabrication and certification plans will be baselined. After the PDR process, the Program will proceed to detailed design, and long-lead-time fabrication and procurement will be authorized.
The detailed design period, in which the bulk of the design and development activity is contained, results in further baselining and puts under configuration control the details of the hardware and software to be fabricated as well as the final test certification requirements at the work package and contractor level. The details of all interfaces will have been incrementally defined and frozen during the detailed design process.

The approach often used for the design and development of advanced space systems involves test articles for development and qualification purposes. Hardware used for these purposes, but not for flight, is called "prototype hardware." In this approach there can be an extensive and severe testing program for the prototype equipment as it is not intended for flight. Furthermore, the flight hardware can be fabricated and assembled as soon as the design drawings are approved, allowing some schedule concurrency between the prototype and the flight article development. In some cases the technology involved permits, or economies require, that the same unit of hardware be used for the entire sequence of design, limited testing, and flight. This is called the "protoflight hardware approach" or "protoflighting." NASA has successfully used both approaches in previous programs and intends a mixed strategy involving both prototype and protoflight hardware for the Space Station Program. The decisions on whether or not to protoflight specific items of Space Station hardware will depend on factors such as technology risk, flight safety, cost differential and schedule risk. These decisions for Space Station hardware development are to be made between PDR and CDR when the details of the requirements and the approaches for hardware development are finalized.

A Critical Design Review (CDR) will be performed for each of the elements. The CDR provides assurance that the detailed designs of flight and ground systems satisfy Program requirements. The primary product of the CDR will be an approved set of engineering documentation defining the design of selected CEIs to be released to manufacturing. As a result of these reviews, authority will be granted to proceed to completion of fabrication and certification of the Station hardware and software. Plans will be finalized for the assembly, checkout, launch, and on-orbit assembly, system verification, and operation.

Near completion of fabrication a Design Certification Review (DCR) will be held. The DCR is a formal technical review to certify design of the CEIs for flight worthiness and manned flight safety. The review will specifically address certification requirements, plans, methods, results, and certification status of flight hardware and software. In this same time frame, the final details associated with pre- and post-launch assembly and checkout will be baselined, and the final plans for validation that the as-built hardware conforms to the as-certified design will be established.

As part of the activity to establish flight readiness, a series of reviews of the operations aspects of the Program, called Preflight Operations Readiness Reviews (PORR), will be performed. These reviews will assure the status of crew and ground support team training, flight and ground console operations, the Space Station Support Complex (SSSC), Program and user support facilities, and the status of NSTS interfaces relative to Station crew and cargo.

The Flight Readiness Review (FRR) will be performed prior to each launch during the assembly phase and will certify the flight readiness of hardware and software. This review will include assembly hardware, crew equipment, Flight Support Equipment (FSE), associated support hardware, payload support equipment, and other elements as specified by the Director of the Space Station Program.

The final step in the development program will be the Operational Readiness Review (ORR) after the on-orbit integration, assembly, and checkout have been completed. As a result of this review, the actual hardware and software performance and capability will be determined, defined, and certified, and the initial detailed operational procedures for the Program at that phase will be baselined.

The total process of system development in phase C/D is depicted in Figure II-1.

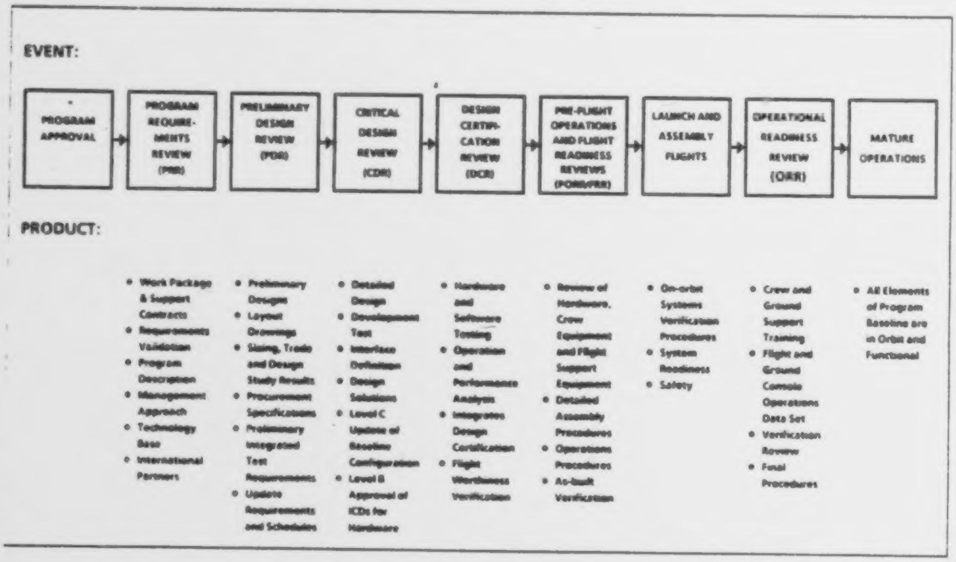

EVENT:
PROGRAM APPROVAL
PROGRAM REQUIREMENTS REVIEW (PRR)
PRELIMINARY DESIGN REVIEW (PDR)
CRITICAL DESIGN REVIEW (CDR)
DESIGN CERTIFICATION REVIEW (DCR)
PRE-FLIGHT OPERATIONS AND FLIGHT READINESS REVIEWS (PORR/FRR)
LAUNCH AND ASSEMBLY FLIGHTS
OPERATIONAL READINESS REVIEW (ORR)
MATURE OPERATIONS
PRODUCT:
• Work Package & Support Contracts
• Requirements Validation
• Program Description
• Management Approach
• Technology Base
• International Partners
• Preliminary Designs
• Layout Drawings
• Sizing, Trade and Design Study Results
• Procurement Specifications
• Preliminary Integrated Test Requirements
• Update Requirements and Schedules
• Detailed Design
• Development Test
• Interface Definition
• Design Solutions
• Level C Update of Baseline Configuration
• Level B Approval of ICDs for Hardware
• Hardware and Software Testing
• Operation and Performance Analysis
• Integrated Design Certification
• Flight Worthiness Verification
• Review of Hardware, Crew Equipment and Flight Support Equipment
• Detailed Assembly Procedures
• Operations Procedures
• As-built Verification
• On-orbit Systems Verification Procedures
• System Readiness
• Safety
• Crew and Ground Support Training
• Flight and Ground Console Operations Data Set
• Verification Review
• Final Procedures
• All Elements of Program Baseline are in Orbit and Functional

Figure II-1. Space Station Phase C-D Events

System Engineering and Integration (SE&I)

A system engineering approach across the total Space Station Program is essential for developing and maintaining a coherent, technically integrated design. The system design, integration, and verification activities must be carefully blended to assure that the Space Station provides the necessary performance required for safe and efficient operations. The Space Station SE&I starts with the development of the system design requirements which are derived from the needs of the scientific community for new experiments to fly in Earth orbit; the needs of advanced-development programs for data from space to validate promising, new technologies; the need for potential new space manufacturing techniques and commercial products; and other space needs of industry and government.

Space Station SE&I controls the definition of elements and distributed systems which are the fundamental building blocks of the Space Station. An element is the largest functional assembly used as a Space Station building block. The U.S. laboratory is an example of an element. A distributed system is one that is required by two or more elements and provides an end-to-end function. The electric power system is an example of a distributed system.

The SE&I approach to the Space Station must define all of the performance characteristics of elements and distributed systems so that they will fit together in orbit and work efficiently to provide an integrated and functional Space Station.

Space Station Program-level SE&I includes the following: analysis of the overall Space Station performance, optimization of user support, definition of the configuration and its supportability, apportioning the performance requirements among the elements and subsystems, controlling the design process, planning the system integration, and conducting the on-orbit assembly and test. The test and delivery of the elements and distributed systems is performed by the participating Centers or the international partners.

A principal SE&I function is to conduct tests of the assembled Space Station on orbit and to validate and document the "as built" configuration to provide a reference for future maintenance, modification, and operation of the completed Space Station.

Close coordination of SE&I with Space Station Information System (SSIS) and other Program functions assures a balanced design. An example of this balance is in the design, number, and location of the cupolas which are required to facilitate proximity operations, EVA, attached payload activities, and Space Station maintenance.

NASA has defined a strategy for the design, development, verification, integration, assembly, launch, and on-orbit validation of the Space Station systems. This strategy involves the following:

- Verification of all systems and elements prior to launch;
- Commonality of test requirements and procedures across work packages;
- Phase C/D contractor execution of verification testing (mandatory accountability);
- Design of simple interfaces to facilitate verification;
- Design for a minimum of on-orbit assembly;
- Design for maintainability and minimum life cycle costs;
- Commonality across work packages in standards, hardware, and procedures to simplify orbital verification and to minimize cost;

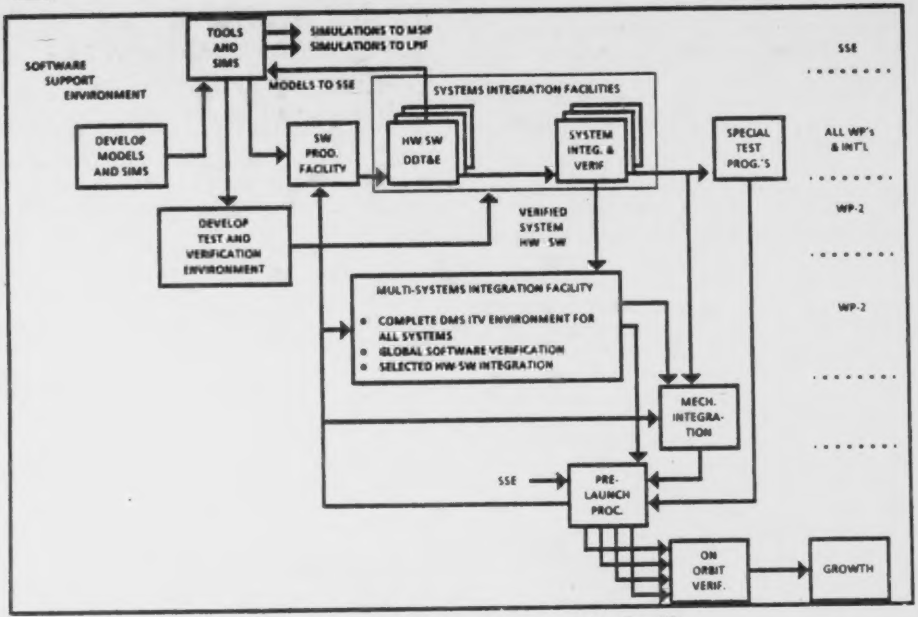

TOOLS AND SIMS
SIMULATIONS TO MSIF
SIMULATIONS TO LPIF
SSE
SOFTWARE SUPPORT ENVIRONMENT
MODELS TO SSE
SYSTEMS INTEGRATION FACILITIES
DEVELOP MODELS AND SIMS
SW PROD. FACILITY
HW SW DDT&E
SYSTEM INTEG. & VERIF
SPECIAL TEST PROG.'S
ALL WP's & INT'L
WP-2
DEVELOP TEST AND VERIFICATION ENVIRONMENT
VERIFIED SYSTEM HW SW
MULTI-SYSTEMS INTEGRATION FACILITY
• COMPLETE DMS ITV ENVIRONMENT FOR ALL SYSTEMS
• GLOBAL SOFTWARE VERIFICATION
• SELECTED HW-SW INTEGRATION
WP-2
MECH. INTEGRATION
SSE
PRE-LAUNCH PROC.
ON ORBIT VERIF.
GROWTH

Figure II-2. Multisystems Integration Facility

- Extensive use of simulators to verify interfaces; and
- Early integration of application software into flight hardware.

Some Space Station subsystems will have functional components located in all major elements. The Data Management System (DMS) is one example of these distributed systems. Complete subsystems must be designed, developed, and validated for the incorporation into different modules and other elements. Each module must also be developed, assembled, and tested as an entity. After deployment of each launch package, the partially completed Station must function as a self-contained spacecraft pending mating of the next launch package.

A Multi-System Integration Facility (MSIF) including a transportable simulation capability is planned for the validation of interfaces with simulated external environments. See Figure II-2. Subsystem contractors will develop models and simulators as well as intrinsic subsystems with embedded software for use by other work package contractors and for incorporation into the MSIF. For the integrated subsystems (DMS, Electrical Power, etc.) contractors will design and develop subsystems as dictated by an Architectural Control Document (ACD). The contractor will assure that the end-to-end system is in consonance with the ACD. Field Center Project Offices supported by their contractors will be responsible for validating the functional performance of their elements and will support the integration of the elements with the rest of the Space Station. The element contractor will be responsible for establishing user compliance requirements and for the integration of user hardware. For example, the U.S. laboratory module contractor will have the responsibility of integrating experiments into racks and the racks into the module. The contractors also will participate in the incorporation of elements into launch packages.

At a checkout facility to be developed at the Kennedy Space Center (KSC), launch packages will be fully evaluated prior to launch as well as tested for compatibility with subsequent launch packages. The launch packages will be assembled on-orbit where final integration and validation tests such as the precise measurements of structural-dynamics modes will occur.

The distributed development strategy involving several contractors will require that the Program standarize certain selected processes and procedures. These processes and procedures must be controlled in the same way as design requirements. The mechanism for this control is through Process Requirements which are issued by the Program Office. Table II-1 is a listing of the current process requirements. One of the more important process requirements deals with commonality.

A Space Station Commonality Program has been initiated to reduce Space Station Program operating costs and the crew time required for training, operations, and maintenance. The Program aims at reduced costs by (a) using existing designed hardware from other programs, (b) using identical or similar designs to satisfy similar functional requirements, (c) reducing the types of spares required, (d) using qualified standard parts, and (e) using common software, hardware, and interfaces. The Space Station Commonality Process Requirements document establishes responsibilities within the Program.

SPACE STATION INFORMATION SYSTEM SERVICES ENGINEERING AND INTEGRATION

NASA has placed significant emphasis on the system engineering and integration of the Space Station Program information systems. These systems include the Technical and Management Information System (TMIS), the Software Support Environment (SSE) system, and the operational Space Station Information System (SSIS). TMIS, a ground-based distributed information system, will be connected through the existing NASA Program Support Communication Network (PSCN) and will allow transmittal of development phase engineering and management information between NASA Program organizations and receipt of data by the field centers from their contractors' facilities. The SSE System will be a ground-based information system which provides the tools for the development, maintenance, and sustaining engineering of Program software and will also be connected through the PSCN. The SSIS will be the operational end-to-end system by which the data flow between the onboard system and ground control or data processing systems and the scientific users will be provided. The SSIS will be a distributed system spanning the total information flow networks required to operate the Space Station. The SSIS will operate via the NASA Communications Network (NASCOM). Although TMIS and SSE are primarily developmental support systems, their connectivity with SSIS will permit valuable operational use. These systems are discussed in more detail in the following sections.

Space Station Information System (SSIS)

The SSIS will provide the operational end-to-end command, control, and

Table II-1. Process Requirements

1. **Maintainability Process Requirements**
2. **Commonality Process Requirements**
3. **Master Verification Process Requirements**
4. **Combined Elements and Integrated Systems Process Requirements**
5. **Customer/Experiments Verification Process Requirements**
6. **Verification Integration Process Requirements**
7. **System Engineering Process Requirements**
8. **Automation and Robotics (A&R) Process Requirements**
9. **Resource Allocation Process Requirements**
10. **Program Cost Management Process Requirements**
11. **Support Equipment Integration Process Requirements**
12. **Interface Development Process Requirements**
13. **Operations Process Requirements**
14. **Contamination Control Process Requirements**
15. **User Integration Process Requirements**
16. **Mission Manifest Process Definition**
17. **Ground Support Equipment Integration Process Requirements**
18. **Space Station Flight Support Equipment and Orbital Support Equipment Integration Process Requirements**
19. **Electromagnetic Effects Control Process Requirements**
20. **Plasma Effects Control Process Requirements**
21. **Ionizing Radiation Effects Control Process Requirements**
22. **Process Requirements for Design Knowledge Capture**
23. **Verification and Installation, Assembly, and Checkout Process Requirements**
24. **Software System Engineering Process Requirements**

informational flow infrastructure between the on-board and the ground-based control and data processing systems. The SSIS will service on-board payloads, sensors, and mechanisms with information processing, archiving, retrieval, and exchange. The SSIS integrates all the data systems and information system services functions required to manage information flow within the Space Station; among customers, crew members, and ground support personnel; and between ground-based functions. The engineering and integration task for the SSIS must assure proper functioning of the on-board systems, such as the Data Management System and the Communication and Tracking System with the NASA space and ground-based communication networks, the Space Station manned base and platform control centers, and the space science payload data processing, archiving, and retrieval system. The SSIS represents a major engineering and management challenge that will require extensive Program interaction with the Office of Space Operations and the Office of Space Science and Applications.

The SSIS engineering and integration approach is to provide information services using an end-to-end system. This approach requires defining the information systems services which must be provided end-to-end (including data classes, priorities, and performance characteristics), standards and interfaces to implement those services, selecting standards from existing national, international, and commercial standards to maximize interoperability with other national and international space endeavors, and applying these requirements to the SSIS development process. Assurance reviews of each SSIS element or sub-network for standards compliance will be conducted, as well as element, sub-network and end-to-end testing of SSIS.

Technical and Management Information System (TMIS)

In view of the distributed nature of the Space Station development program and the numerous technical and organizational interfaces, the Program will implement TMIS to improve Program efficiency and data reliability and to support timely decision making. The TMIS will include a backbone data communications network, data processing systems, integrated software tools, and Program-wide data bases which will provide both technical and management users with ready access to information.

The TMIS acquisition strategy is to utilize commercially available, competitively procured products which will not require development of system hardware of software. TMIS will bring on the existing base of NASA data processing and data communications capabilities to achieve maximum return on previous investments. To design, to develop, to operate, and to maintain TMIS, NASA has competitively selected Boeing Computer Services as an integration contractor. The eight-year contract began on June 4, 1987.

NASA intends to use TMIS throughout the life of the Program as the primary mechanism for maintaining, distributing, and archiving controlled data among the three levels of NASA management and the Program Support Contractor (PSC) and to provide information system interfaces with the international partners, the development contractors, and Space Station users. TMIS will be incrementally developed to support the definition, design, development, test, and operational phases of the Space Station Program. Incremental implementation of TMIS will allow NASA to avoid technical obsolescence by incorporating into the TMIS architecture newly emerging technology as it becomes commercially available.

To support the variety of TMIS users, the system capabilities will include project scheduling, resource management and control, requirements development and traceability, configuration management, problem tracking, computer aided design and engineering analysis, design knowledge capture, electronic mail, calendars, documentation, data security, and archival. Using these capabilities, TMIS will provide a repository of Space Station Program-wide management, engineering, design, operational, and user payload information. Program-wide data base requirements for TMIS will be generated by Information Planning Groups.

Software Support Environment (SSE) System

The primary goal of the SSE System is to minimize the operational costs at minimum risk.

Achievement of the minimum cost and risk goal will depend on a software development and maintenance environment (known as the SSE System) that will be standardized for the Program. The major components of the SSE System are the software tools, the SSE Development Facility, and the Software Production Facilities. The SSE Development Facility will be used to develop and maintain the SSE software requirements, design and test tools, compilers, debuggers, models, and simulations. SSE software tools will be used by each Software Production Facility to develop, integrate, and maintain the Program ground and flight software. The SSE System will be developed incrementally with its capabilities time-phased to meet essential Program needs.

The SSE System will provide complete and consistent support for the development, integration, and maintenance of Program software.

Transportation

The Space Station configuration is based on NSTS capabilities for transportation to and from low Earth orbit. The Shuttle launches the elements of the Space Station, provides a stable base from which astronauts can assemble the Station, resupplies the Station through periodic logistics missions, and provides the means for crewmembers to travel to and from the Space Station.

Another space vehicle, the OMV, will be used to provide additional capability to the Space Station Program and to the utilization of the Station. The OMV will be capable of functions which greatly enhance the Space Station including bringing other satellites to the Station for servicing and returning them to their operational orbits and remotely servicing satellites in nearby orbits. The Shuttle carries the OMV to the Station, and after completion of the mission, it returns the OMV to the ground to be refurbished.

NASA is conducting studies of U.S. Expendable Launch Vehicles (ELV)s that would complement the projected NASA baseline of five flights to the Space Station per year in mature operations. The potential role identified for ELVs is the resupply of consumables. Logistic elements launched by ELVs in the future might rendezvous with an OMV that would ferry the logistic element to the Station. ELVs are also being considered for launching polar orbiting platforms.

The assembly sequence described in Appendix A is the current plan. Studies are under way for the use of other vehicles functioning in conjunction with the Shuttle for Space Station assembly.

The addition of attached payloads, experiment equipment for the pressurized modules, spare parts, and expendables will require delivery missions throughout the operational lifetime of the Space Station. The return of manufactured products and equipment for refurbishment will require use of the NSTS. Efforts will continue to minimize these transportation requirements.

Operations Capability

Space Station operations encompass all activities required to assemble and maintain the Space Station and platforms for the planned lifetime. These activities include prelaunch and post-landing processing, crew and ground personnel training, tactical and increment planning, onboard and ground support of station operations, resupply and return logistics operations, communications and data management, trajectory maintenance, and the rendezvous and proximity operations for vehicles and free-flyer satellites. Integration of users with the Program and support to user operations are also provided.

Reviews of flight and ground systems requirements for operations suitability will be conducted in advance of Program design reviews so that their results may be incorporated in decisions and tradeoffs. This is important to ensure that the requirements and design are responsive to the users' needs and that the systems can be operated efficiently and effectively.

In the development phase of the Program, an operations infrastructure will be developed concurrently with the flight hardware and software. This infrastructure will consist of a management structure, a trained work force, and a set of unique support facilities and will be based on recommendations of the Space Station Operations Task Force chartered by the Office of Space Station (OSS). Requirements and design reviews for each facility are planned. Milestones for operations facilities are keyed to the Program schedule for operations.

Space systems operations include the safe operation and maintenance of the Space Station to provide resources and capabilities for users. Planning and real-time support for space systems operations will be provided by a centralized organization supported by engineering and maintenance expertise at the four U.S. WPCs and international partner locations. The Support Services Control Center will be at the JSC. Its capabilities include telemetry processing and storage for systems monitoring and analysis; activity planning and scheduling; resources and consumables management; and trajectory maintenance and maneuver targeting.

The Space Station Support Center (SSSC) will be supported by Engineering Support Centers (ESC)s at the work package centers. During on-orbit verification the centers will have a real-time support capability to monitor and analyze hardware and software; to support the SSSC in troubleshooting problems; to develop maintenance procedures; and to perform sustaining engineering.

User planning and integration activities are distributed throughout many countries, government organizations, private companies and universities. For near-term planning and real-time operations, user activities are coordinated and supported by a Program organization. The Payload Operations Integration Center (POIC) at the Marshall Space Flight Center (MSFC) will have the capability to support various levels of computerized payload planning and will serve as the users' interface to the SSSC. Users and user sponsors will develop their own infrastructure.

The Space Station Platform Support Center (SSPSC), to be at the Goddard Space Flight Center (GSFC), will perform the POIC and support functions for the platforms under funding by other Programs.

Prelaunch processing of hardware elements of the Space Station and platforms and logistics carriers will be carried out at the launch site. Post-landing operations for logistics carriers and cargo is a responsibility of the launch center. The Space Station Processing Facilities (SSPF) will be located at KSC with capabilities for integrating and testing system elements and payload-to-system element interfaces. Payloads and Station cargo will be physically integrated with the logistics carriers here.

Integrated logistics planning will be conducted at the launch site with logistics management being the responsibility of the work packages and contractors. A phased transfer of logistics management responsibility from the developing center to the launch site will take place. Existing facilities at KSC will be used initially for logistics operations. A logistics information system will be developed to support them. A capability to support logistics operations after logistics management responsibility transfer is planned, and it will include such items as inventory management, automated test equipment, and repair capability.

Numerous capabilities for crew training will be used. These capabilities include part-task systems trainers, manipulator and proximity operations simulators, one-G mockups and trainers, and neutral buoyancy facilities. The Space Station systems operations, manipulator and proximity operations, and ground controller training will be centralized at the Space Station Training

Facility (SSTF) at JSC. The SSTF will have the capability to train crews and ground controllers for nominal Space Station systems proximity and manipulator operations as well as response to off-nominal situations. The trainers and simulators will be linked together with NSTS facilities to conduct nominal and contingency integrated simulations during assembly. Joint onboard and ground integrated simulations may be conducted during mature operations phases to maintain crew and ground controller readiness.

Space Station Evolution

With a useful life spanning decades, the Space Station will experience many changes. Commercial, scientific, and technology users will better understand the long term advantages of the space environment on experiments and manufacturing processes and will likely require enhanced Station capability. Some user needs may diminish; others will increase, and still others may be entirely new.

In examining this process, NASA concluded that the Space Station must be designed and constructed in a manner that allows response to changing user needs. Evolution of the Station comprises those changes that increase its capability to meet user needs. This increase can occur in physical growth of the structure, more modules, more laboratory space, more accommodations for attached payloads, or increased productivity and efficiency of Space Station systems and subsystems.

Specific design provisions or "scars" will be incorporated to allow increases in resources and the addition of new functional capabilities. Flexibility for growth will be a major factor in decisions on the Space Station configuration as well as system and subsystem designs. Whenever possible, system and subsystem designs that facilitate the later incorporation of new technologies will be selected. An evolutionary, advanced technology program has been established to develop technologies that will increase Space Station productivity and support expansion of the Station capabilities.

B. MANAGEMENT APPROACH

Management Overview

The Space Station Program will use a three-tiered management structure. The three levels are as follows: Level I, the Office of the Associate Administrator for the Office of Space Station (OSS) at NASA Headquarters in Washington, D.C.; Level II, the Space Station Program Office in nearby Reston, Virginia; and Level III, the field center Project Offices. This structure is shown in Figure II-3.

The Associate Administrator for the Office of Space Station at NASA Headquarters, Level I, is responsible for the overall management and strategic planning of the Program. The organization of this Office is shown in Figure II-4. Principal management responsibilities include policy direction, budget formulation, external affairs, and Space Station evolution. The Associate Administrator will establish and control Level I technical and management requirements, milestones, and budget allocations and forecasts. Coordinating external affairs with both legislative and executive branches, user communities, international partners, and NASA Headquarters that support the Program also falls under the jurisdiction of the Level I Office of the Associate Administrator.

The Space Station Program Office, Level II, (Figure II-5) is responsible for development of the Space Station and the operational capability of flight and ground systems and the control of internal and external interfaces. Principal responsibilities include system engineering and analysis, Program planning and resource control for both development and operations phases, configuration management, and integration of elements and payloads into an opera-

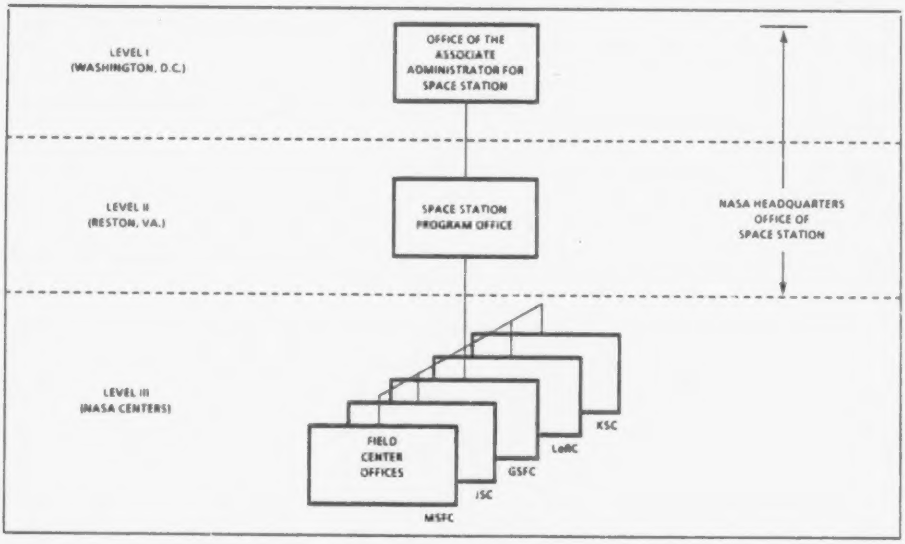

LEVEL I
(WASHINGTON, D.C.)
OFFICE OF THE ASSOCIATE ADMINISTRATOR FOR SPACE STATION
LEVEL II
(RESTON, VA.)
SPACE STATION PROGRAM OFFICE
NASA HEADQUARTERS OFFICE OF SPACE STATION
LEVEL III
(NASA CENTERS)
FIELD CENTER OFFICES
KSC
LeRC
GSFC
JSC
MSFC

Figure II-3. Space Station Organization

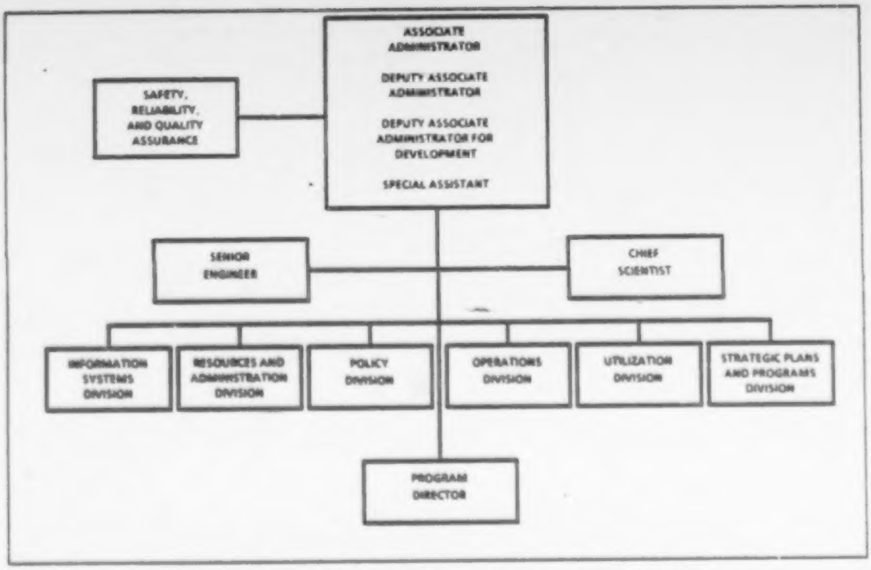

ASSOCIATE ADMINISTRATOR
DEPUTY ASSOCIATE ADMINISTRATOR
DEPUTY ASSOCIATE ADMINISTRATOR FOR DEVELOPMENT
SPECIAL ASSISTANT
SAFETY, RELIABILITY, AND QUALITY ASSURANCE
SENIOR ENGINEER
CHIEF SCIENTIST
INFORMATION SYSTEMS DIVISION
RESOURCES AND ADMINISTRATION DIVISION
POLICY DIVISION
OPERATIONS DIVISION
UTILIZATION DIVISION
STRATEGIC PLANS AND PROGRAMS DIVISION
PROGRAM DIRECTOR

Figure II-4. Office of Space Station Organization

ting system. This Office is headed by the Director, Space Station Program, who is responsible for the day-to-day management. The SSPO is assisted by the PSC and by the TMIS and SSE contractors. The Jet Propulsion Laboratory (JPL) provides an independent Program requirements and assessment function.

Level III consists of the various field center Space Station Projects Offices. These Offices are responsible for Design, Development, Testing and Evaluation (DDT&E); operation of hardware and software systems; and element, evolution, and engineering support. The Project Managers of these Offices report to the Director, Space Station Program.

Center Directors advise the Associate Administrator, Office of Space Station, on technical and management issues and assure institutional excellence and support for their portion of the Program. They also participate as members of a Space Station Management Council. This Council meets regularly with the Associate Administrator and the Program Director on programmatic and institutional matters.

While the SSPO is an organizational element of Headquarters, it is physically separated from the Office of Space Station. While the Associate Administrator has overall Program responsibility, the activities of the Level I Office focus largely on external functions. Examples include international policies, budget development and defense, and congressional activities. On the other hand, the responsibilities of the SSPO are generally internal, relating to implementation of the Program. Examples include design reviews; configuration change and budget control; and development, test, and verification procedures.

Work Package Center (WPC) Responsibilities

In 1986, General Samuel Phillips, former Apollo Program Director, chaired a committee to review the Program's overall management structure and work package responsibilities. The Phillips Committee recommendations were structured to maintain contractor accountability for the planned Phase C/D. Accountability is essential to cost control and demands clearly definable deliverable items that can be integrated and checked out independently. It also requires the assignment of the entire design and development responsibility for each deliverable item to a single contractor.

The Phillips Committee recommended the following development assignments to each work package:

–All pressurized modules, nodes, and tunnels to WP 1, MSFC;
–The truss and its associated systems to WP 2, JSC;
–The platforms and servicing facility to WP 3, GSFC; and
–The power modules and power management system to WP 4, Lewis Research Center (LeRC).

These assignments resolved issues regarding overlap and duplication of work by placing the WP 1, MSFC contractor in the role of the single module developer and the single module integrator for the Program.

Because the assignment of the habitation module to WP 1 caused a skill mix problem within NASA, the committee recommended that WP 2, JSC provide technical direction to WP 1, MSFC contractor for the design and development of Man Systems. This recommendation solved the NASA skill mix issue and made optimum use of the existing institutional facilities and test beds without diffusing the accountability of the WP 1, MSFC contractor for producing a fully outfitted habitation module.

Further review in the fall of 1986 resulted in a refinement to the field centers' development responsibilities which had been recommended by the Phillips Committee. The following is a summary of the current work package

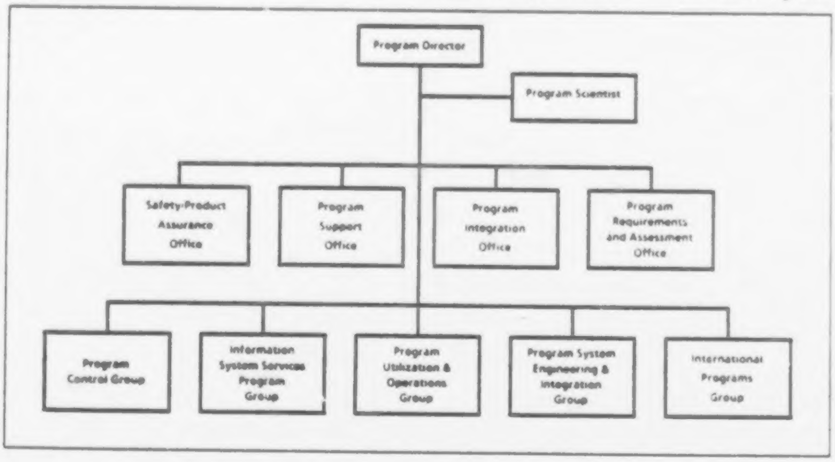

Program Director
Program Scientist
Safety/Product Assurance Office
Program Support Office
Program Integration Office
Program Requirements and Assessment Office
Program Control Group
Information System Services Program Group
Program Utilization & Operations Group
Program System Engineering & Integration Group
International Programs Group

Figure II-5. Space Station Program Office

assignments: The responsibility for the Station laboratory, habitation module, logistics elements, and the resource node primary structure fabrication is assigned to WP 1, MSFC. The external truss, distributed subsystems, EVA systems, airlock and resource node design and outfitting are assigned to WP 2, JSC. Responsibility for Space Station platforms, attached payload accommodations, the Flight Telerobotic Servicer (FTS), and NASA's role in servicing is assigned to WP 3, GSFC. The power system is assigned to the WP 4, LeRC. WP 1, MSFC, through its contractor, has overall responsibility for the Space Station laboratory and habitation module. WP 2, JSC continues to exercise its responsibility for the manned space subsystems through special provisions within the MSFC contract. Similar provisions are established in the JSC contract. Technical and management responsibility for the engine elements of the Space Station's propulsion system rests with WP 1, MSFC.

Centers responsible for a distributed system issue a system design in the form of an ACD which guides other centers (Table II-2). These ACDs are under Level II documentation control.

In the Space Station Program, system integration is managed by the Level II office which assures that all subsystems will fit together and function as a single unit.

The SSPO was established to provide strong, central program management to conduct system integration and resolve differences among centers. A control board system, discussed in more detail below under Change Control, has been implemented to review and approve all system documentation to the Program baseline including interfaces shown in Table II-3. The review process includes consideration of design options, technology risk, supportability, safety, and both development and operations costs. Each Level II board has a responsibility in the overall cost management process.

International

Management of the potential international elements will be conducted within the framework of both bilateral inter-governmental agreements and agency-to-agency Memoranda of Understanding (MOU)s which are currently under negotiation. The management structure will be set forth in these agency-to-agency agreements. Documentation plans and major reviews are specified therein. Potential international partners will be technically and financially responsible for Space Station hardware. Management mechanisms will be established to coordinate activities of all partners and to reach agreement on requirements.

Bilateral Program Coordination Committees (PCC)s, established during the

Table II-2. Architectural Control Documents

1. Electric Power System
2. Data Management System
3. Thermal Control System
4. Communication and Tracking
5. Guidance, Navigation, and Control
6. Environmental Control and Life Support System
7. Extra-Vehicular Activity
8. Man Systems
9. Fluids
10. Assembly and Maintenance
11. Servicing

definition phase, will meet during the design and development phase to review respective design, development, operation and utilization activities. At that time decisions will be made to assure implementation of the cooperative activities of the international partners. The Associate Administrator for Space Station and his international counterpart will co-chair each PCC. The co-chairs will each designate their respective members. Joint PCC meetings may be held when specified issues require consideration by another partner at that level.

Liaison activities with international partners will be conducted under the direction of the NASA Office of the Associate Administrator. Under the terms of applicable agency-to-agency MOUs, each partner may provide representatives to the OSS, located at NASA Headquarters in Washington, D.C., to coordinate cooperative Program activities. Likewise, NASA is entitled to such representation at the respective partner's Headquarters sites. To facilitate the implementation of the cooperative program, each partner will provide, under the terms of applicable agency-to-agency agreements, liaison representation at the Space Station Program Office site in Reston, VA. Likewise, the SSPO will provide liaison representation at the respective partner's Program Office. As required on a case-by-case basis, partners may provide liaison representation to specific Space Station Program field office sites to support the implementation of the cooperative program. NASA may also provide, where required, liaison to partner field office sites.

Table II-3. Program Interfaces

ELEMENT/ELEMENT INTERFACES

1. Node/Modules
2. Attached Payload Accommodations/Truss Assembly
3. Service Facility/Truss Assembly
4. Power Module/Truss Assembly
5. Module/Truss Assembly
6. Telerobotic Servicer/Space Station
7. Logistics Carrier (Pressurized)/Space Station
8. Logistics Carrier (Unpressurized)/Space Station
9. Element/KSC Facility
10. Element/KSC GSE
11. Element/FSE

INTERNATIONAL INTERFACES

1. JEM Elements/Space Station
2. Columbus Laboratory/Space Station
3. MSC/Transporter
4. MSC/Space Station
5. MSC Maintenance Depot/Space Station

EXTERNAL PROGRAMS INTERFACES

1. NSTS/Space Station
2. OMV/Space Station
3. GPS/Space Station
4. TDRSS/Space Station

Program Control

The elements of program control which include schedules, resources, and configuration control will be implemented by the SSPO and the project offices.

The management of schedules will be implemented through the establishment of controlled milestones at various levels of the Program. Each controlled milestone will be assessed on a continuous basis by the field center project offices and the SSPO. Any change to the controlled milestones will require formal approval. The Program has established an intersite delivery schedule between each of the implementing project offices. These establish when specific hardware is required to be delivered from one project office to another to meet schedule milestones. These intersite delivery dates are established by the Space Station Schedules Working Group chaired by the SSPO with representation from each of the field center project offices. This group will review the intersite delivery schedules on a continual basis to assess potential problem areas and required adjustments.

All contracts of $25M or greater will have in place a Performance Measurement System (PMS). The PMS will provide the capability to assess the contract performance for both cost and schedule on a monthly basis.

The management and control of financial resources will involve several processes. Management has established a baseline for budget and schedules for the development phase. A detailed phased operating plan will be developed for the operating year, and Program progress against the plan will be reviewed on a monthly basis. The field center project offices will provide cost status and schedule progress to the SSPO. The SSPO will assess the projected budget requirements quarterly and semiannually with the field center project offices. Based on this review the Program Director will make recommendations to the Associate Administrator on the development and operations budget. The recommendations form the basis for the review with Agency management and subsequent budget submission to OMB and Congress.

The SSPO will also review technical changes submitted to the configuration control process for their impacts on development and operations costs and schedule.

The integration of the schedules and cost will be accomplished by utilizing the Development WBS which has been baselined for the Program. There will be an updated WBS based on the data to be provided by the development contractors.

Change Control

The change process will be handled at each level through a formal documentation and board structure.

Top level Program requirements are established by Level I and documented in the Program Requirements Document. These requirements will be controlled by the Program Control Board chaired by the Associate Administrator. Level II program and technical requirements including content, schedule, and interface requirements are contained in the Program Definition and Requirements Document and related sub-tier documents. These documents add technical detail to the Level I requirements. The process for establishing and controlling these documents is founded on a formal configuration management discipline using a Level II Space Station Control Board (SSCB).

The SSCB is chaired by the Program Director. Membership includes the

SSPO functional directors, the Level III Project Managers, other key managers, and the international participants. In practice, the board becomes the top-level authority for reviewing and controlling the Program baseline. The Level II SSCB is supplemented by other SSCB chartered boards and panels to handle work activity in various areas. See Figure II-6. Formally controlled, SSP Level II baseline documentation will be maintained by the SSPO. Proposed additions or changes to the baseline will be made through Space Station Program Level II change requests signed by an SSCB member or the member's authorized representative and forwarded to the SSCB Executive Secretary. The Level II Screening Group, chaired by the SSCB Executive Secretary and comprised of representatives from the SSCB member areas, will review all change requests for completeness, determine the appropriate method for processing, and designate the SSCB member organizations whose evaluations are considered mandatory for change request disposition. The Screening Group Chairman will assign and forward change requests to the appropriate sub-board for evaluation and/or disposition. Change requests deemed within the scope of the board charter may be processed outside of the board in accordance with pre-established criteria or may be dispositioned by the board chairman at a scheduled meeting. The Chairman may recommend that the change request be processed outside of the board in accordance with pre-established criteria or may be dispositioned by the board

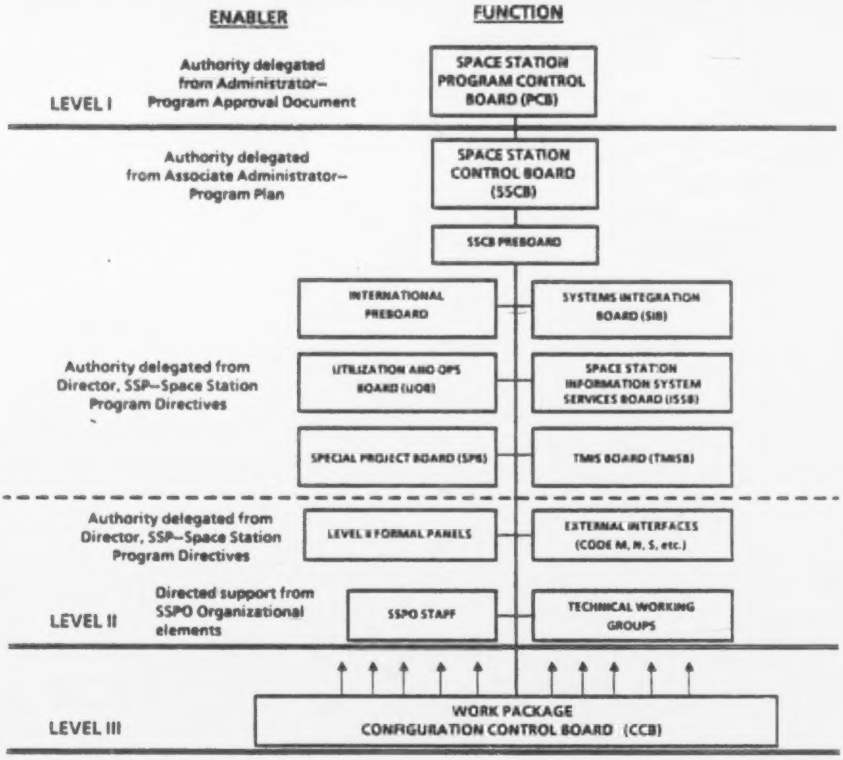

ENABLER
FUNCTION
LEVEL I
Authority delegated from Administrator–Program Approval Document
SPACE STATION PROGRAM CONTROL BOARD (PCB)
Authority delegated from Associate Administrator–Program Plan
SPACE STATION CONTROL BOARD (SSCB)
SSCB PREBOARD
INTERNATIONAL PREBOARD
SYSTEMS INTEGRATION BOARD (SIB)
Authority delegated from Director, SSP–Space Station Program Directives
UTILIZATION AND OPS BOARD (UOB)
SPACE STATION INFORMATION SYSTEM SERVICES BOARD (ISSB)
SPECIAL PROJECT BOARD (SPB)
TMIS BOARD (TMISB)
Authority delegated from Director, SSP–Space Station Program Directives
LEVEL II FORMAL PANELS
EXTERNAL INTERFACES (CODE M, N, S, etc.)
LEVEL II
Directed support from SSPO Organizational elements
SSPO STAFF
TECHNICAL WORKING GROUPS
LEVEL III
WORK PACKAGE CONFIGURATION CONTROL BOARD (CCB)

Figure II-6. Space Station Control Boards Structure/Interfaces

chairman at a scheduled meeting. The Chairman may recommend that the change request be processed through another authorized board or may forward the change request to the SSCB Chairman for review and final disposition. In the event that the board chairman recommends processing through another authorized board, the change request will be submitted to the SSCB Executive Secretary with the appropriate recommendation. The SSCB Executive Secretary will again provide the change request to the Level II Screening Group with a recommendation for redirection. The Executive Secretary of the board shall be responsible for preparing and distributing minutes and directives and updating the action item tracking list. The change process is depicted in Figure II-7. At each field center Level III project, a similar process is in place with the Project Manager chairing a Configuration Control Board (CCB) to control changes within the project.

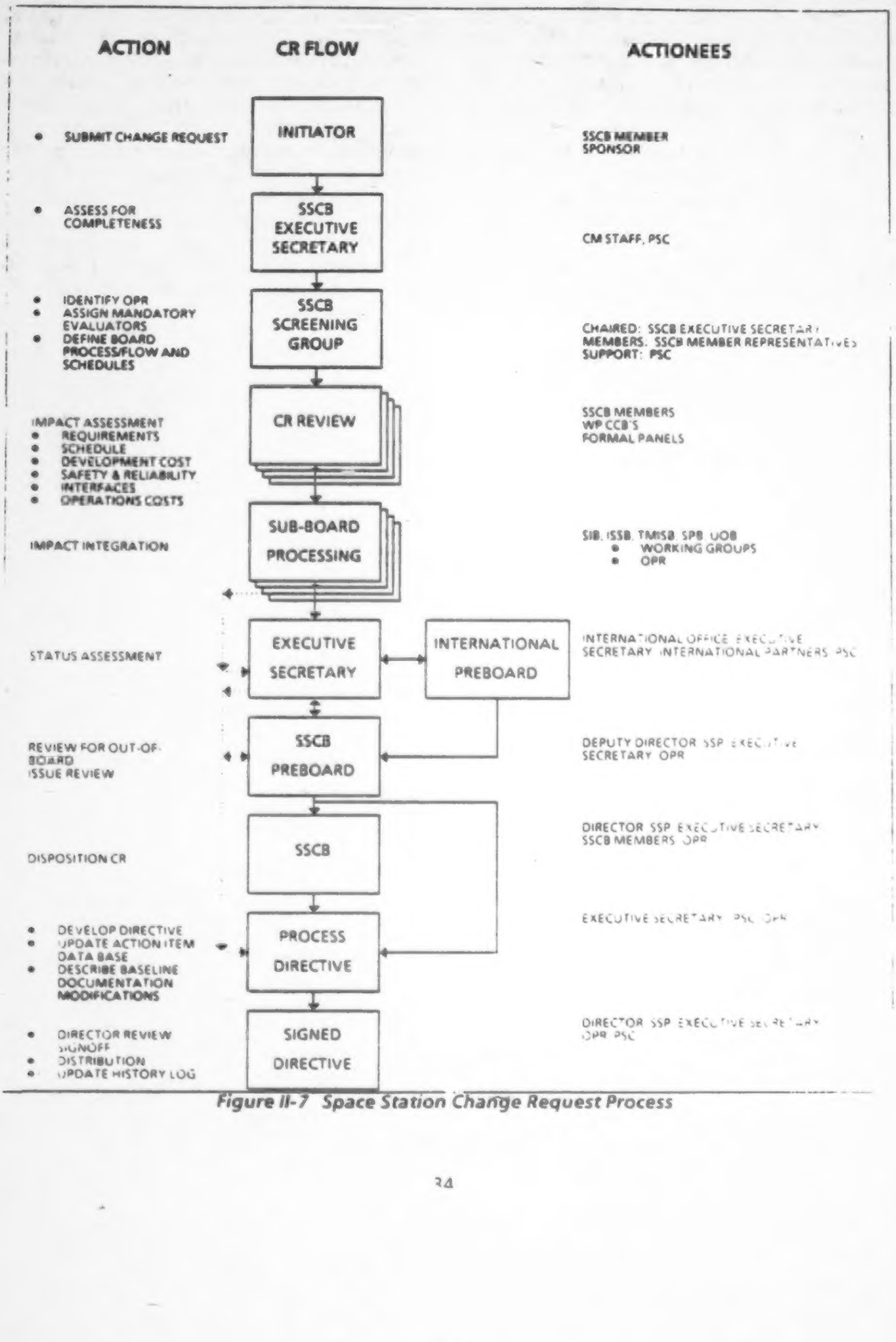

ACTION
CR FLOW
ACTIONEES
SUBMIT CHANGE REQUEST
INITIATOR
SSCB MEMBER
SPONSOR
ASSESS FOR COMPLETENESS
SSCB EXECUTIVE SECRETARY
CM STAFF, PSC
IDENTIFY OPR
ASSIGN MANDATORY EVALUATORS
DEFINE BOARD PROCESS/FLOW AND SCHEDULES
SSCB SCREENING GROUP
CHAIRED: SSCB EXECUTIVE SECRETARY
MEMBERS: SSCB MEMBER REPRESENTATIVES
SUPPORT: PSC
IMPACT ASSESSMENT
REQUIREMENTS
SCHEDULE
DEVELOPMENT COST
SAFETY & RELIABILITY
INTERFACES
OPERATIONS COSTS
CR REVIEW
SSCB MEMBERS
WP CCB'S
FORMAL PANELS
IMPACT INTEGRATION
SUB-BOARD PROCESSING
SIB, ISSB, TMISB, SPB, UOB
WORKING GROUPS
OPR
STATUS ASSESSMENT
EXECUTIVE SECRETARY
INTERNATIONAL PREBOARD
INTERNATIONAL OFFICE, EXECUTIVE SECRETARY, INTERNATIONAL PARTNERS, PSC
REVIEW FOR OUT-OF-BOARD
ISSUE REVIEW
SSCB PREBOARD
DEPUTY DIRECTOR SSP, EXECUTIVE SECRETARY, OPR
DISPOSITION CR
SSCB
DIRECTOR SSP, EXECUTIVE SECRETARY
SSCB MEMBERS, OPR
DEVELOP DIRECTIVE
UPDATE ACTION ITEM DATA BASE
DESCRIBE BASELINE DOCUMENTATION MODIFICATIONS
PROCESS DIRECTIVE
EXECUTIVE SECRETARY, PSC, OPR
DIRECTOR REVIEW SIGNOFF
DISTRIBUTION
UPDATE HISTORY LOG
SIGNED DIRECTIVE
DIRECTOR SSP, EXECUTIVE SECRETARY
OPR, PSC

Figure II-7 Space Station Change Request Process

The Program Support Contractor (PSC)

NASA has recently awarded a level-of-effort, task-order contract to provide necessary skills to support the Space Station Program Office in Reston, VA and at the participating field centers. The scope of the contract is broad and includes support in both programmatic and technical activities in all Level II functional areas. The principal effort, however, will be to assist NASA in the essential SE&I functions, including program requirements analysis and assessment, systems engineering and analysis, distributed systems integration, technical integration, and element and launch package integration. The PSC will provide additional support to areas such as design of the ground communication and the ground-to-space communication links, the planning of interfaces with users, and the development of concepts and facility plans for the use and operation of the Space Station.

A Contract Administrator has been assigned to the SSPO to manage the PSC. Task monitors have been assigned in each functional area of the SSPO. The contract duration extends one year after completion of on-orbit assembly. To motivate PSC performance, the contract contains provisions for periodic evaluations and award-fee determination by NASA. The PSC will establish its principal operating site in close proximity to the SSPO in Reston, VA and will have offices at each of the participating centers.

Operations Management

Because of the breadth, duration, and international nature of Space Station operations, a unique organizational structure has been recommended for the effective management of utilization and operations activities. Its primary feature is a strong, centralized, technically competent operations planning and integration activity (Figure II-8). The activities will be strategically managed and tactically integrated in Washington with international participation, and supported and implemented at the centers.

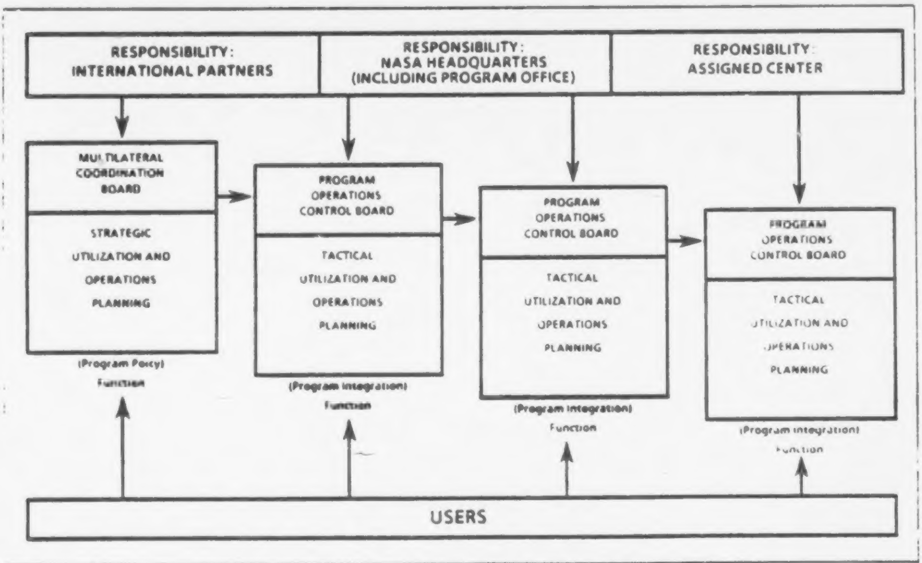

RESPONSIBILITY: INTERNATIONAL PARTNERS
RESPONSIBILITY: NASA HEADQUARTERS (INCLUDING PROGRAM OFFICE)
RESPONSIBILITY: ASSIGNED CENTER
MULTILATERAL COORDINATION BOARD
STRATEGIC UTILIZATION AND OPERATIONS PLANNING
(Program Policy) Function
PROGRAM OPERATIONS CONTROL BOARD
TACTICAL UTILIZATION AND OPERATIONS PLANNING
(Program Integration) Function
PROGRAM OPERATIONS CONTROL BOARD
TACTICAL UTILIZATION AND OPERATIONS PLANNING
(Program Integration) Function
PROGRAM OPERATIONS CONTROL BOARD
TACTICAL UTILIZATION AND OPERATIONS PLANNING
(Program Integration) Function
USERS

Figure II-8. Operations Management

For the U.S. allocation of Space Station resources, the Space Station Users Board (SSUB) will conduct utilization and operations planning for five year periods. The Board will include membership from NASA user sponsoring organizations (OSSA, OAST, OCP, etc.), other government agencies, and commercial reimbursable users. Each Space Station partner will submit its five year plan. The Multilateral Control Board, supported by the User Operations and System Operations Panels (established by MOUs) will produce a five year Consolidated Utilization Plan (CUP).

The CUP is then used by the SSPO to generate a two-year Tactical Operations Plan (TOP) (Figure II-9). Tactical operations planning covers a two year period and includes manifests, milestones, payload integration, safety reviews, documentation, installation, test, checkout procedures, ground flow, and logistics support. The development of the TOP will be supported by a Space Station Users Working Group and other Station accommodations working groups. A Payload Accommodations Manager (PAM) will be assigned to each payload in the CUP. The PAM will be a single point of contact for an individual user of the Space Station. The approved TOP is the basis for the generation of multiple increment plans, where an increment is defined as the period of time between NSTS visits to the Station (Figure II-10). NASA field centers, international partners, and user operations facilities execute the increment plan as well as support the integrated tactical management functions.

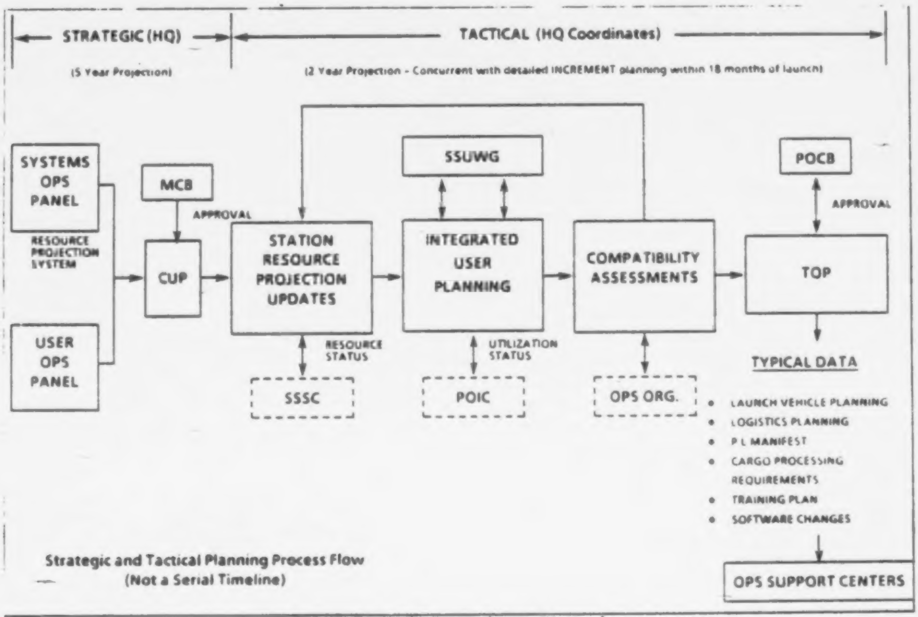

STRATEGIC (HQ)
(5 Year Projection)
TACTICAL (HQ Coordinates)
(2 Year Projection - Concurrent with detailed INCREMENT planning within 18 months of launch)
SYSTEMS OPS PANEL
RESOURCE PROJECTION SYSTEM
USER OPS PANEL
MCB
APPROVAL
CUP
STATION RESOURCE PROJECTION UPDATES
RESOURCE STATUS
SSSC
SSUWG
INTEGRATED USER PLANNING
UTILIZATION STATUS
POIC
COMPATIBILITY ASSESSMENTS
OPS ORG.
POCB
APPROVAL
TOP
TYPICAL DATA
• LAUNCH VEHICLE PLANNING
• LOGISTICS PLANNING
• P L MANIFEST
• CARGO PROCESSING REQUIREMENTS
• TRAINING PLAN
• SOFTWARE CHANGES
OPS SUPPORT CENTERS
Strategic and Tactical Planning Process Flow
(Not a Serial Timeline)

Figure II-9. Operations Planning

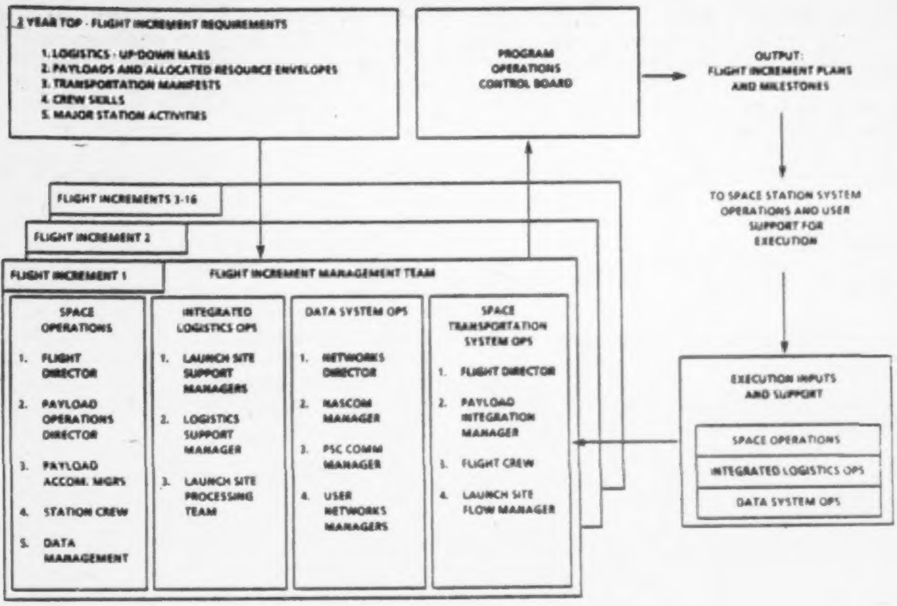

2 YEAR TOP - FLIGHT INCREMENT REQUIREMENTS
1. LOGISTICS - UP-DOWN MASS
2. PAYLOADS AND ALLOCATED RESOURCE ENVELOPES
3. TRANSPORTATION MANIFESTS
4. CREW SKILLS
5. MAJOR STATION ACTIVITIES
PROGRAM OPERATIONS CONTROL BOARD
OUTPUT: FLIGHT INCREMENT PLANS AND MILESTONES
TO SPACE STATION SYSTEM OPERATIONS AND USER SUPPORT FOR EXECUTION
FLIGHT INCREMENTS 3-16
FLIGHT INCREMENT 2
FLIGHT INCREMENT 1
FLIGHT INCREMENT MANAGEMENT TEAM
SPACE OPERATIONS
1. FLIGHT DIRECTOR
2. PAYLOAD OPERATIONS DIRECTOR
3. PAYLOAD ACCOM. MGRS
4. STATION CREW
5. DATA MANAGEMENT
INTEGRATED LOGISTICS OPS
1. LAUNCH SITE SUPPORT MANAGERS
2. LOGISTICS SUPPORT MANAGER
3. LAUNCH SITE PROCESSING TEAM
DATA SYSTEM OPS
1. NETWORKS DIRECTOR
2. NASCOM MANAGER
3. PSC COMM MANAGER
4. USER NETWORKS MANAGERS
SPACE TRANSPORTATION SYSTEM OPS
1. FLIGHT DIRECTOR
2. PAYLOAD INTEGRATION MANAGER
3. FLIGHT CREW
4. LAUNCH SITE FLOW MANAGER
EXECUTION INPUTS AND SUPPORT
SPACE OPERATIONS
INTEGRATED LOGISTICS OPS
DATA SYSTEM OPS

Figure II-10. Increment Planning

Operations Cost Management

NASA recognizes that cost-effective operation of the Space Station, both manned base and platforms, is essential. A plan for managing operations costs has been prepared and is being submitted separately to the committee on Science, Space and Technology. Key features of the plan are an organizational structure facilitating operations cost management; identification and control of significant cost drivers; implementation of tools, procedures, and processes for managing costs; and innovative, evolutionary application of A&R. A clearer focus on operations costs is being provided through the establishment of a separate line for operations in the Space Station budget. A model has been developed to estimate categories of operations costs (e.g., logistics, ground operations) and will be used to predict and assess the effect of Program changes on operations costs. A control board system that reviews and approves all changes to the Program baseline has been implemented. The review process includes consideration of design options, technology risk, supportability, and both development and operations costs. Each Level II board has a responsibility in the overall cost management process.

Construction of Facilities (CoF)

Facility construction requirements are submitted by the field centers to the Space Station Facility Review Board which is chaired by the SSPO with representation from the project offices. This board provides recommendations to the Director, Space Station Program, who provides a complete facility program recommendation to the Associate Administrator, Office of Space Station. The Program priorities are then tied with the agency priorities.

Table II-4 identifies the planned facility projects through FY89. The Program annually reviews requirements for outyears and adjusts its facility project recommendations to meet programmatic changes.

Management Reviews

At Level I a monthly Program Review is held along with regular meetings of the Space Station Management Council. The NASA Administrator conducts a monthly General Management Status Review. This series of reviews is designed to keep management fully informed of both progress and problems and to provide information for timely decisions.

Monthly reviews are routinely held at Level II and Level III Program organizations having responsibility for the development and control of a delegated portion of the NASA baseline configuration to ensure that all higher level and interface requirements have been incorporated into the baseline. These reviews provide management an opportunity to assess progress and to initiate actions to correct problems that arise.

Table II-4. Office of Space Station

CONSTRUCTION OF FACILITIES PLAN

PROJECT	LOCATION	START (FY)
Human Performance Research Laboratory	ARC	1987
System Integration and Mock-up Laboratory	JSC	1987
Space Power systems Laboratory	LeRC	1987
Mods to TS300 for Oxygen/Hydrogen Test	MSFC	1987
Space Station Processing Facility	KSC	TBD
Mission Control Center Addition (SSCC)	JSC	TBD
Simulator-Trainer Addition (SSTF)	JSC	TBD
Automated Integration and Assembly Facility	JSC	TBD

C. PROCUREMENT APPROACH

Background

NASA strategy for procurement emphasizes competition and phasing. Separate Space Station procurements were conducted for Phase A (Requirements and Architecture) and Phase B (Definition and Preliminary Design). At present a competitive procurement is under way for Phase C/D (Detailed Design and Development). During the Phase B development of requirements and conceptual design, competitive procurements were awarded for eight, fixed-price contracts. NASA awarded two concurrent 21-month contracts for each of four work packages managed by NASA field centers. NASA awarded a number of contracts for technology development in a Program termed "Advanced Development." Overall development strategy for the Space Station included a major effort in technology concurrent with the preliminary design. Four key activities were emphasized: focused technology, prototype development, test beds, and flight experiments. Candidate technologies from the advanced development program have been evaluated and incorporated into the procurement process for the development phase.

Strategy

In planning the transition from definition to development, NASA decided to recompete the contracts for the four WPCs rather than "downselect" from among the Phase B contractors. This approach allowed NASA an opportunity to evaluate more thoroughly the results of Phase B and to refine the plans for Phase C/D.

The procurement strategy for the Program development phase is designed as a distributed program consisting of four work packages. Four work package RFPs were released in April of 1987, and proposals were received in September. They are now under evaluation. Each RFP calls for bids against the Program and a phased option with a description of how private sector investment would be integrated with the baseline activity.

The distributed work package approach allows for wide participation by U.S. aerospace industry. Contractor teaming for the different work package elements and systems expands private-sector involvement and broadens resources available to the Program such as the capital investment into aerospace facilities and peripheral areas.

As noted earlier, the absence of a prime contractor and the retention by NASA of the primary responsibility for SE&I avoids the necessity for a long-term contractual commitment with a major Program hardware systems contractor. In-house SE&I makes good use of NASA technical skills and capabilities to build into the agency the corporate memory necessary to manage the Program. NASA in-house integration also minimizes the possibility of duplicating design and development costs while more fully integrating NASA-wide technology and research and development expertise.

The development phase includes eight major procurements. In accordance with federal procurement procedures, opportunities for small businesses and minority-owned enterprises are available. The eight development procurements, some of which have been concluded, are as follows:

(1) a work package design and development contract to be awarded by each of the four WPCs, (2) a TMIS contract that provides common access to the Program data base, (3) an SSE contract that provides the set of tools to be used for life-cycle management of all Space Station software, (4) a PSC to provide

support across the program during Phase C/D, and (5) an FTS contract. All of these contracts are planned to be of the cost-plus-award-fee type except the FTS which for Phase B will be on a fixed-price basis. The NASA Administrator has been designated as the Source Selection Official for all of these procurements except FTS where the Associate Administrator will be the selection official. Operations capability development projects are planned at JSC, MSFC, KSC, GSFC, and LeRC. Each of these centers will develop a procurement approach that best fits its other operations facilities and needs.

Because of the distributed nature of Space Station procurement activities, an extensive effort continues on the part of the SSPO to provide coordination among all NASA participants in major procurements. Where appropriate, common reference documents, common requirements, and common contractual provisions were established and used across the procurements. Each participating center was given the opportunity to review and provide comments on the RFP from each of the other centers. Finally, each RFP was formally reviewed and approved by NASA Headquarters before release to industry. Source Evaluation Board membership at each center included representation from the other participating NASA centers. A Space Station Program Procurement Coordination Committee consisting of representatives from the SSPO, all participating centers, and NASA Headquarters General Counsel and Procurement Offices was established to provide a steering mechanism to ensure consistency among procurement activities.

The PSC, TMIS, and SSE contracts, all of which will be managed by NASA Headquarters, have been awarded to major U.S. aerospace firms. Proposals for the FTS and proposals for the work package procurements received in September 1987 are currently being evaluated.

D. SAFETY AND PRODUCT ASSURANCE

Introduction

Safety is of paramount concern to NASA in the development of the Space Station. Ensuring the well-being of the Station crew is an objective that permeates nearly every aspect of its planning. Although risk cannot be eliminated from space flight, it can be understood and minimized. Ultimately, the Program will have to balance risk, cost, and benefits. A concerted effort will be made to assure that Space Station operations are safe. The Space Station Safety, Reliability, Maintainability, and Quality Assurance (SRM&QA) program has been designed to take advantage of lessons learned from past programs. The Space Station, however, has many unique characteristics and requirements which challenge the state of the art in SRM&QA management philosophies and techniques. Factors related to long life, safety, and product assurance include the following:

(a) An on-orbit equipment failure must be rapidly identified and located.
(b) The Space Station must have an across-the-board capability for restorability in the event of failures while at the same time being able to sustain a variety of normal user operations.
(c) The Space Station consists of many large, complex, and diverse elements that must be assembled and activated on orbit over a period of many space missions. The final system integration and verification activities will take place on orbit.
(d) The Space Station developmental and operational costs must be kept to reasonable levels consistent with the safety and/or reliability requirements.

Rigorous implementation of SRM&QA requirements and procedures will result in safe, reliable, long-life Space Station operations.

The Space Station Program safety and product assurance requirements are defined and controlled by the Space Station Program Requirements Document and the Space Station Program Definition and Requirements Document. The Space Station Safety and Product Assurance Program is also based on policies and requirements as set forth in the agency-level management documents. Implementation plans for Space Station safety and product assurance are defined and specified in Safety and Product Assurance Program Plans which are prepared by Levels II and III and by the Space Station contractors.

Space Station international partners will generate their own safety and product assurance requirements documents and implementation plans. These requirements and plans will be equivalent to or exceed corresponding NASA safety and product assurance requirements. NASA personnel will be permitted to participate, as necessary, in design review and technical meetings conducted by Space Station international partners. In accordance with the international agreements currently being negotiated, NASA will have the ultimate responsibility for the safety of the Space Station and will be the final authority on all issues relating to safety.

The Space Station Safety and Product Assurance Manager for Level I is a collocated assignment from the Associate Administrator for SRM&QA to the Associate Administrator for the Office of Space Station. The Level I Safety and Product Assurance Manager is responsible for advising the Space Station Associate Administrator on Program SRM&QA requirements policy and issues in an independent manner while maintaining a role as an integral member of the Space Station management organization. Safety and product assurance organizations at both Level II and Level III will also be collocated to various project offices. Level II will also have direct support for all SRM&QA functions from the Space Station PSC. Level III will ensure that the work package contractors have the appropriate SRM&QA requirements in subcontractor contracts and purchase orders and assure compliance therewith. The Level III Safety and Product Assurance Managers will utilize the Department of Defense contract administration offices for direct safety, reliability, and quality assurance support and surveillance at manufacturing locations. In all cases the product assurance and safety organizations are collocated with the Program and project offices and retain direct access to the senior Program or project manager. For all significant SRM&QA concerns, issues, and policy matters, the SRM&QA Managers have direct, unimpeded access to the senior SRM&QA institutional management.

The safety and product assurance organizations at all levels are also significantly involved in the contractor award fee processes. The Associate Administrator for SRM&QA is a member of the Award Fee Determination Board thereby ensuring that appropriate consideration for SRM&QA input receives the highest level of consideration during the award fee determination process.

The Safety and Product Assurance Offices at each level will have members on the appropriate change control boards. As a result, each change will be examined for SRM&QA implications. As board members the Safety and Product Assurance Managers will have the responsibility and authority to assure that changes will be consistent with the SRM&QA objectives.

Safety

Program safety objectives will identify and evaluate Space Station design and operational activities to assure that measures are taken to minimize risks. The system safety objectives include performing safety analyses to identify the hazards associated with hardware, software, and operations during all Program phases; assuring that proper design and performance requirements eliminating or controlling the identified hazards are developed, documented, and implemented; and performing an overall risk assessment including the identification of residual hazards and/or risks.

Safety requirements will be incorporated into system design, operations, and procurement documentation including facilities, Ground Support Equipment (GSE), and flight hardware and software. A verification system will be used to maintain current requirements documents and reference the next higher or lower requirement document, assure specific requirements are imposed, and report implementation status of requirements.

Safety analyses will be performed for the purpose of identifying the hazards associated with the hardware, software, and operational environments. The analyses will be evaluated, and the resultant actions will be considered by the CCB. The analyses shall identify hazardous conditions, causes, effect, controls, and verification methods. Operating and support hazard analyses will address events associated with the fabrication, assembly, test, checkout, launch, use, maintenance, disposal, and on-orbit operations.

The foremost consideration will be to remove hazardous sources and operations. Corrective action priorities will be established to reduce potential for personnel and material losses. Actions for satisfying safety engineering requirements will be in the following order of precedence:

(1) Hazard elimination. The hazard source or the hazardous operation will be eliminated.
(2) Design for Minimum Hazard. The major goal throughout the design phase will be to ensure inherent safety through provisions of appropriate design features, materials and parts selection, and safety factors. Damage control, containment, and isolation of potential hazards and failure tolerance considerations are to be included in design considerations.
(3) Safety Devices. Known hazards that cannot be eliminated by design will be reduced to an acceptable level by incorporating safety devices as part of the system, subsystem, or equipment.
(4) Warning Devices. Where it is not possible to preclude the existence or occurrence of a known hazard, warning devices will be employed for the timely detection of hazardous conditions and the generation of adequate warning signals.
(5) Special Procedures. Where it is not possible to reduce the magnitude of an existing or potential hazard by design or by use of safety and warning devices, special procedures will be developed to counter hazardous conditions for enhancement of ground and flight crew safety.
(6) Personnel Protective Clothing and Equipment. Protective clothing and equipment to minimize the effects of potential hazards will be provided.

Space Station safety organizations will, on a selective basis, perform (or cause to be performed) independent assessment(s) of hazard dispositions and/or residual hazards.

Other safety activity areas include the following: hazard closure criteria, human engineering, industrial safety, test operations safety, required safety certifications and approvals, and flight operations safety.

Reliability and Maintainability

The prime functions of Space Station reliability organizations will be to assure compliance with the following reliability goals: critical hardware and/or functions will be two-failure tolerant; Space Station hardware will be serviceable on orbit and restorable, on orbit, including replacement in the event of failure; conservative design margins will be established vis-a-vis performance requirements; Space Station designs will utilize best available state-of-the-art preferred parts, components, etc., to meet design objectives; and Space Station systems performance will be fully verified by a combination of test, analysis, and simulation prior to launch.

A major focus of Space Station reliability activities will center on Failure Modes and Effects Analyses (FMEA)s. Critical item controls have been established for the test and verification of requirements and contingency procedures have been developed in the event that failures should occur during operation.

Other major reliability activity areas are described in detail in the Space Station Program Definition and Requirements Document and include reliability design criteria, critical Item control, limited life control, supplier control, verification assurance, maintainability assurance, and reliability participation in design reviews and engineering control boards and panels.

Electrical, Electronic, and Electromechanical (EEE) parts will be selected on the basis of suitability for their applications and proven qualifications. Selection shall minimize the number of styles and generic types and will emphasize parts with proven technologies and inherent reliability. Approved parts for Space Station are specified in published standards and all non-standard parts will require a non-standard part approval. All selected parts will be supported by qualification at the parts level.

EEE parts will be procured from approved sources to assure that all applicable requirements are met. A consolidated procurement approach which considers cost, availability, and commonality will be a major consideration for EEE parts control and acquisition.

Over an operating life of several decades, it is an assumption that any element of the Space Station could experience a failure. The Space Station must be designed to accommodate maintenance requirement as various functional systems will be replaced due to obsolescence and technological advancement.

The capability to restore failed hardware to a fully operational state safely and efficiently is a fundamental design and operational requirement for Space Station. Accordingly, all Space Station hardware must be designed for restorability and on-orbit servicing.

The Space Station criteria for achieving of desired restorability characteristics include the following:

(1) the development of a Program maintenance concept which addresses operational availability, repair versus replacement policy, level of replacement, skill-level requirements, sparing concept (i.e., on-board vs deliverable), standardization policy and practice, testability and diagnostic principles and concepts, accessibility requirements, and crew time considerations,

(2) the definition of required maintenance and servicing characteristics and capabilities to be incorporated into the Space Station design;

(3) the identification and definition of maintenance and servicing tasks that are likely to be required over the operating life of the Space Station;

(4) the requirement for contractors to prepare maintenance and servicing plans to support the established maintenance and servicing concept;

(5) the requirement for contractors to determine optimal Orbital Replacement Unit (ORU) configurations based on analysis of performance requirements, safety considerations, reliability, cost, fault detection and diagnostic requirements, accessibility requirements, unit replacement times, and weight/volume considerations;

(6) contractors will be required to demonstrate compliance with required maintenance and servicing capabilities; and

(7) any Space Station critical hardware element or function that cannot be safely and efficiently restored on orbit is a deviation from Program requirements that must have signature approval of the Director, Space Station Program.

Quality Assurance

The prime function of quality assurance is to assure that all hardware, software, and services to be procured by the Space Station Program are defined by properly prepared specifications and drawings and that all such hardware and services comply with the specifications and drawings. Major activity areas within the Space Station quality assurance discipline include design and development controls, procurement controls; manufacturing and fabrication controls; inspection, test and verification controls; metrology and calibration controls; cleanliness and contamination controls; handling/storage/marking/labeling/packaging/shipping controls; and problem reporting, corrective action, trend analyses and recurrence control programs.

Verification requirements will be defined and specified as an integral part of Space Station hardware and software procurements. Compliance with the requirements will be checked by verification, test, simulation, analysis, and inspection.

To the extent feasible, Space Station performance and functional requirements will be verified by test. Each specific performance and/or functional requirement (including maintenance and servicing requirements) will be verified by test and submitted to the Space Station Program Director for approval.

The Space Station test program includes the traditional categories of development, qualification, acceptance, and launch processing and flight tests. Because Space Station final integration and assembly takes place on orbit new approaches to test verification will be required. Similarly, new and innovative approaches will be developed to verify the capability to perform on-orbit maintenance and servicing tasks.

Detailed plans and requirements for establishing and implementing the Space Station verification program will be contained in a Space Station Master Verification Plan and its sub-tier documents.

Lessons Learned

An ongoing component of the Space Station Safety and Product Assurance Program is a review of safety and product assurance activities from previous programs. The Associate Administrator for SRM&QA is sponsoring a study of the lessons learned that will systematically analyze the findings of the Challenger accident investigations to determine the specific applicability of "Lessons Learned" to the Space Station Program. The initial phase of this study is scheduled for completion late this year.

E. PROGRAM SCHEDULE

The Space Station Program schedule is based on the goal of attaining a First Element Launch (FEL) no later than March 31,1994 with a permanently Manned Capability achieved early in 1996. Contract Start Date (CSD) for the Phase C/D detailed design and hardware development phase is targeted for November, 1987. The top-level Space Station milestones are shown in Table II-5.

Milestones

Figures II-11A, 11B, and 11C depict a near-term schedule through the summer of CY 1988. As shown, upcoming milestones include the completion of the major Program procurements, the fiscal budget submissions, completion of international negotiations and documentation, and a number of non-prime and facility-related activities.

Within the Program plan, a Program schedule has been established for use in contractor proposals and Program planning. These milestones and a more detailed set of supporting milestones have been designated as controlled milestones. They are incorporated in the Program Definition and Requirements Document and come under the formal change control procedures of that document. The current milestone dates are as shown in Table II-6.

Intersite Delivery Schedules

Distributed development responsibilities within the Program dictate the need for clear accountability and scheduling of element and system components as they move through the integration process. The interdependence of hardware and software schedules requires careful integration. A key component of the plan is the intersite delivery schedule. For each deliverable end item, these schedules depict the assembly flight assignment, the work package or entity responsible for delivery, the launch date, and intermediate deliveries necessary to complete assembly, integration and verification. Table II-7 is representative of the intersite delivery schedules.

Table II-5. NASA Space Station Schedule Plan

Milestone	Commitment Date
WP Contract Start	November 1987
First Element Launch	March 31, 1994
Man-Tended Capability	March 31, 1995
Permanently Manned Capability	**Early 1996**

Figure II-11a. Space Station Program Office Working Schedule

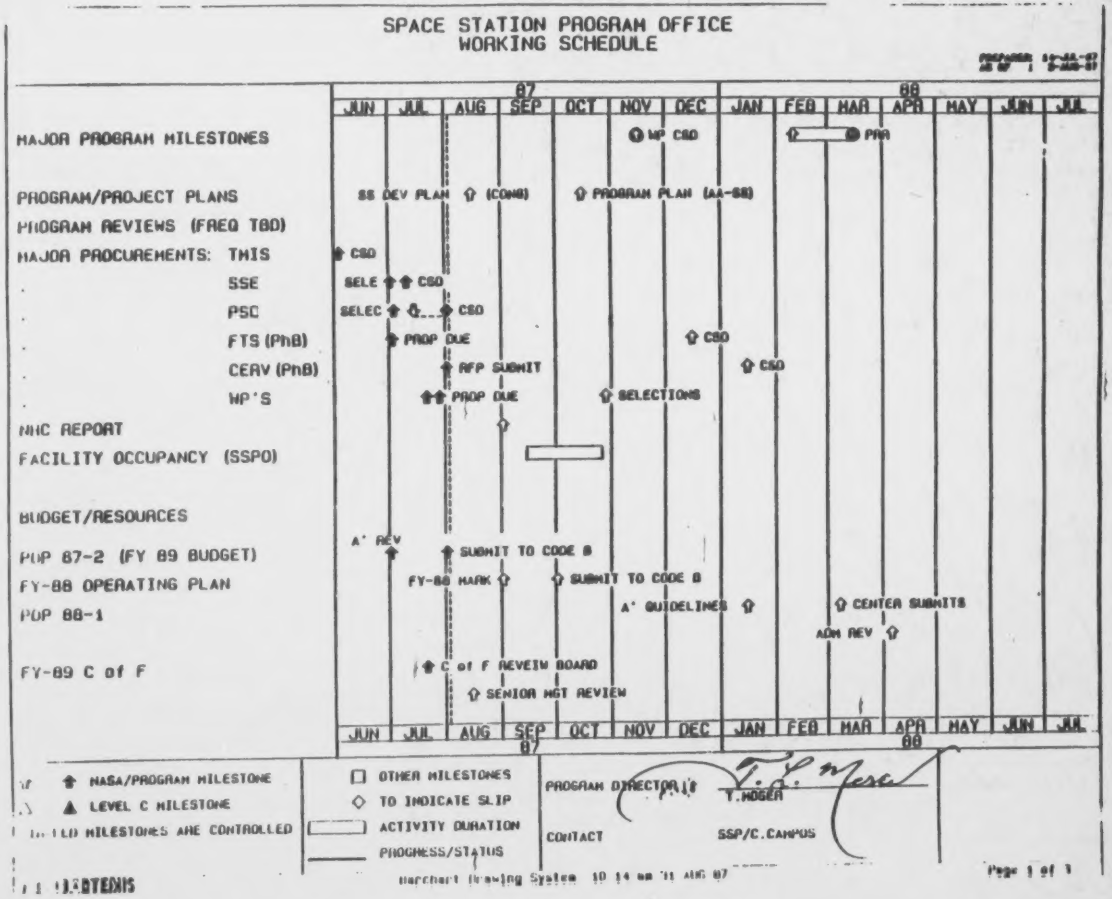
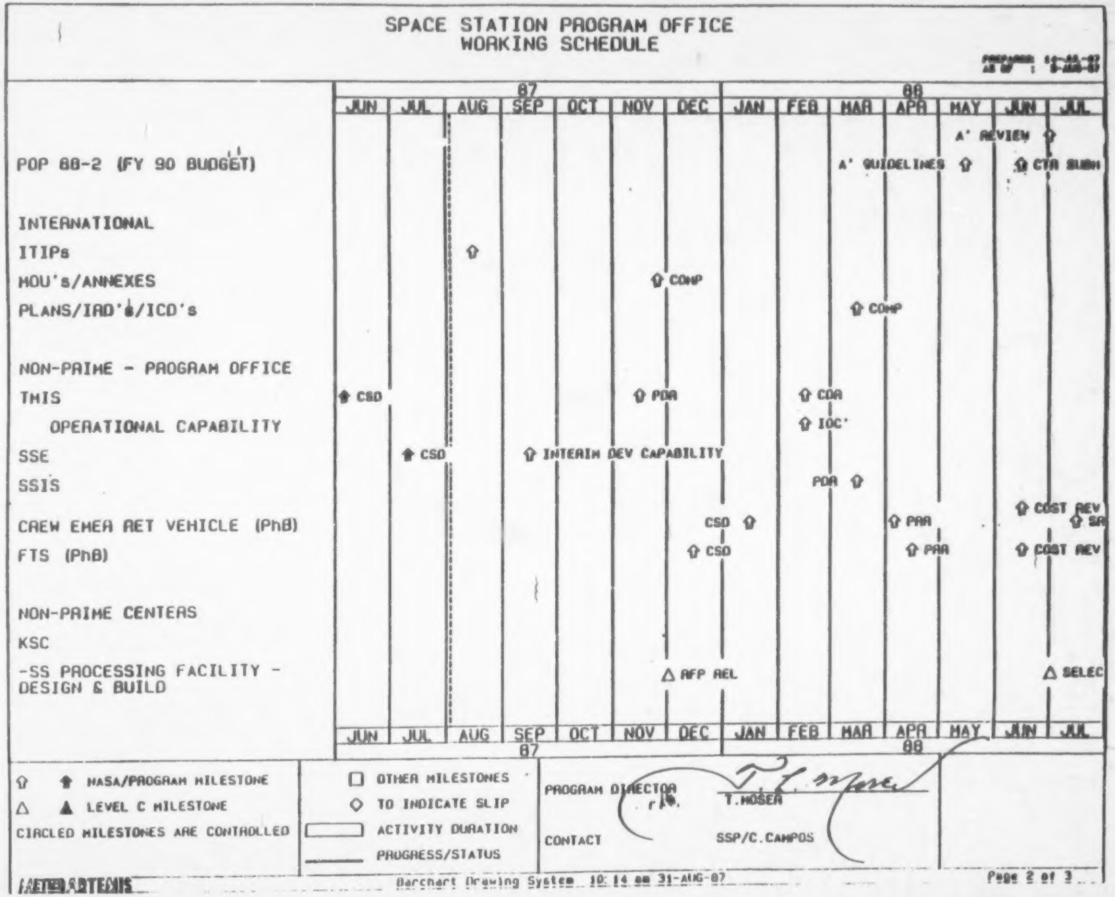


Figure II-11b. Space Station Program Office Working Schedule



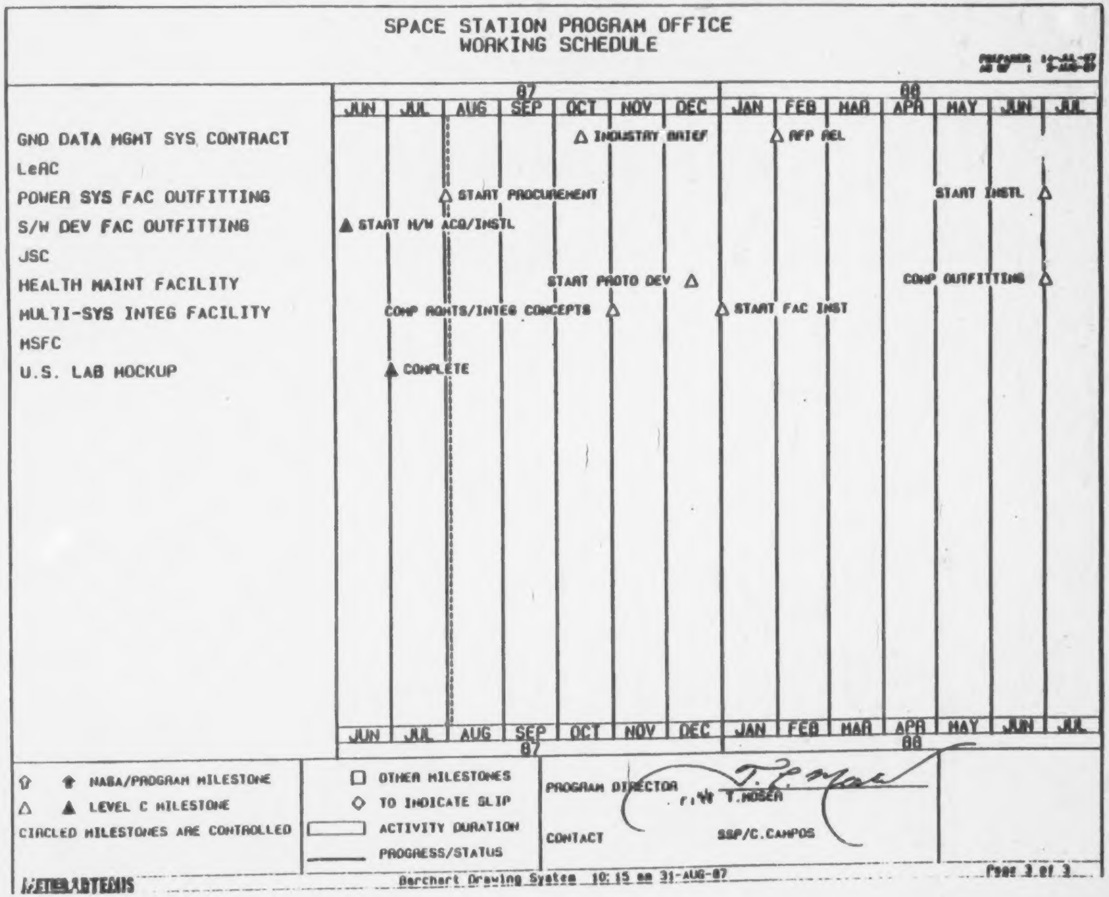


Figure II-11c. Space Station Program Office Working Schedule

Table II-6. Space Station Milestones

Milestone (under review)	Date
Phase C/D Contract Start Date, CSD	November 1987
Preliminary Requirements Review, PRR	March 1988
Flight Systems Requirements Review	March 1988
Operations Capability Requirements Review (Initial)	May 1988
Preliminary Design Review, PDR	January 1989
Operations Capability, PDR (Initial)	January 1989
Ground Systems Requirements Review	March 1989
Operations Capability, CDR (Initial)	January 1990
Operations Capability Requirements Review (Final)	February 1990
Critical Design Review, CDR-1	August 1990
Operations Capability, PDR (Final)	January 1991
Critical Design Review, CDR-2	June 1991
Operations Capability, CDR (Final)	July 1991
Critical Design Review, CDR-3	March 1992
Operations Facility Readiness Review (Initial)	June 1992
Operations Facility Readiness Date (Initial)	July 1992
Design Certification Review, DCR-1	October 1992
Design Certification Review, DCR-2	October 1993
Design Certification Review, DCR-3	January 1995
Pre-Flight Operations Readiness Review, PORR	July 1993
First Flight Readiness Review, FFRR	October 1993
Operations Facility Readiness Review (Final)	November 1993
Operations Facility Readiness Date (Final)	December 1993
First Element Launch, FEL	March 1994
Man-Tended Capability, MTC	January 1995
Permanently Manned Capability, PMC	October 1995
U.S. Polar Platform Launch	November 1995
Assembly Complete	November 1996
Operational Readiness Review	January 1997

TABLE II-7 (SAMPLE)
(PRELIMINARY) INTERSITE DELIVERIES
WORK PACKAGE I AS OF 10 JULY 1987

END ITEM/DELIVERABLE	FLT NO.	FROM WP NO.	TO WP1	TO WP2	TO WP3	TO WP4	TO JAPAN	TO ESA	TO CAN	LAUNCH SITE O/D	LAUNCH DATE
Reso Node #1 – Structure	1	1		L-25							
Standard Racks	1	1		L-31							
ECLSS	1	1		L-25							
Internal Audio	1	1		L-27							
Internal Video	1	1		L-27							
Internal Thermal	1	1		L-25							
Common GSE	1	KSC	L-39								
Unique GSE	1	1		L-25							
Berthing Mechanism	1	1		L-25							
Hatch & Hatch Mechanism	1	1		L-24							
Manned Systems (MSSCH)	1	1		L-25							
Special Transportation System	1	KSC	L-27								
Reso Node #2 – Structure	2	1		L-24							
Standard Racks (Exc C&T)	2	1		L-30							
Standard Equipment Rack for C&T	2	1		L-34							
ECLSS	2	1		L-24							
Internal Audio	2	1		L-30							
Internal Video	2	1		L-30							
Internal Thermal	2	1		L-24							
Common GSE	2	KSC	L-32								
Unique GSE	2	1		L-24							
Berthing Mechanism	2	1		L-24							
Manned Systems (MSSCH)	2	1		L-24							
Hatch & Hatch Mechanism	2	1		L-25							
Special Transportation System	2	KSC	L-26								
Airlock (Standard) – ECLSS	3	1		L-25							

APPENDIX A
SYSTEM DESCRIPTION

This appendix describes the manned base and the platforms and discusses the on-orbit assembly sequence. This design and the assembly sequence will undergo some changes as development progresses. Also included is a brief discussion of the definition study of a Crew Emergency Return Vehicle (CERV) although it is currently not part of the Program.

Design of the Space Station has been driven to a large extent by analysis of user requirements. Payload accommodation assessments have been conducted for all payload disciplines including the potential categories of large space structures and future Program support. Assessments of materials-processing and life-science microgravity payloads have played a major role in the configuration of the Space Station and location of the laboratory modules. By designing a mass balanced configuration, it will be possible to achieve a microgravity environment.

Astrophysics and Earth observation payloads require mounting locations with unobstructed fields of view. Open areas of the transverse boom will provide sufficient space to support servicing and assembly of attached payloads and free flyers. The expansion of the truss size, from 3 to 5 meters, provides a substantial increase in optimum pointing payload locations.

During the definition phase, the length of the U. S. laboratory was increased to better accommodate payload volume requirements. The current module can accommodate up to 42 cubic meters (30 double racks) of payloads and payload support equipment. The atmospheric pressure in the laboratories and habitation module was fixed at 14.7 psi (sea-level pressure) in response to user requests to avoid the necessity for expensive reestablishment of ground-based experiment data.

Data system parameters have been sized to meet initial payload requirements and provide room for growth. The driver for Space Station payload data transmission is the transfer, storage, and downlink of digital television from externally mounted payloads (22 to 44 Mbps). Instruments for the polar platform may require up to 300 Mbps of data transmission. The power capability of the Station has been sized to support multiple high power (7 to 20 kw) payloads, in particular materials processing furnaces, other materials processing facilities, and plasma physics payloads.

The number of crewmembers which the Station is designed to support is directly related to both the size of the modules and the anticipated workload. This crew support capability will be complemented by extensive payload automation support and the use of artificial intelligence. Support for the use of robotics in payload installation, resupply, and repair outside the modules will be provided. Internal robotic elements will be supported by the Data Management System (DMS). Figure A-1 depicts the configuration and identifies the responsibilities of the NASA field centers and the potential international partners for elements and systems. The design features a 110-meter-long horizontal boom in the middle of which are attached three pressurized laboratories and a habitation module. Photovoltaic arrays generating a total average power of 75 kw are located at the ends of the boom. Two attachment points for external payloads are provided along this boom. There will be a telerobotic servicer and

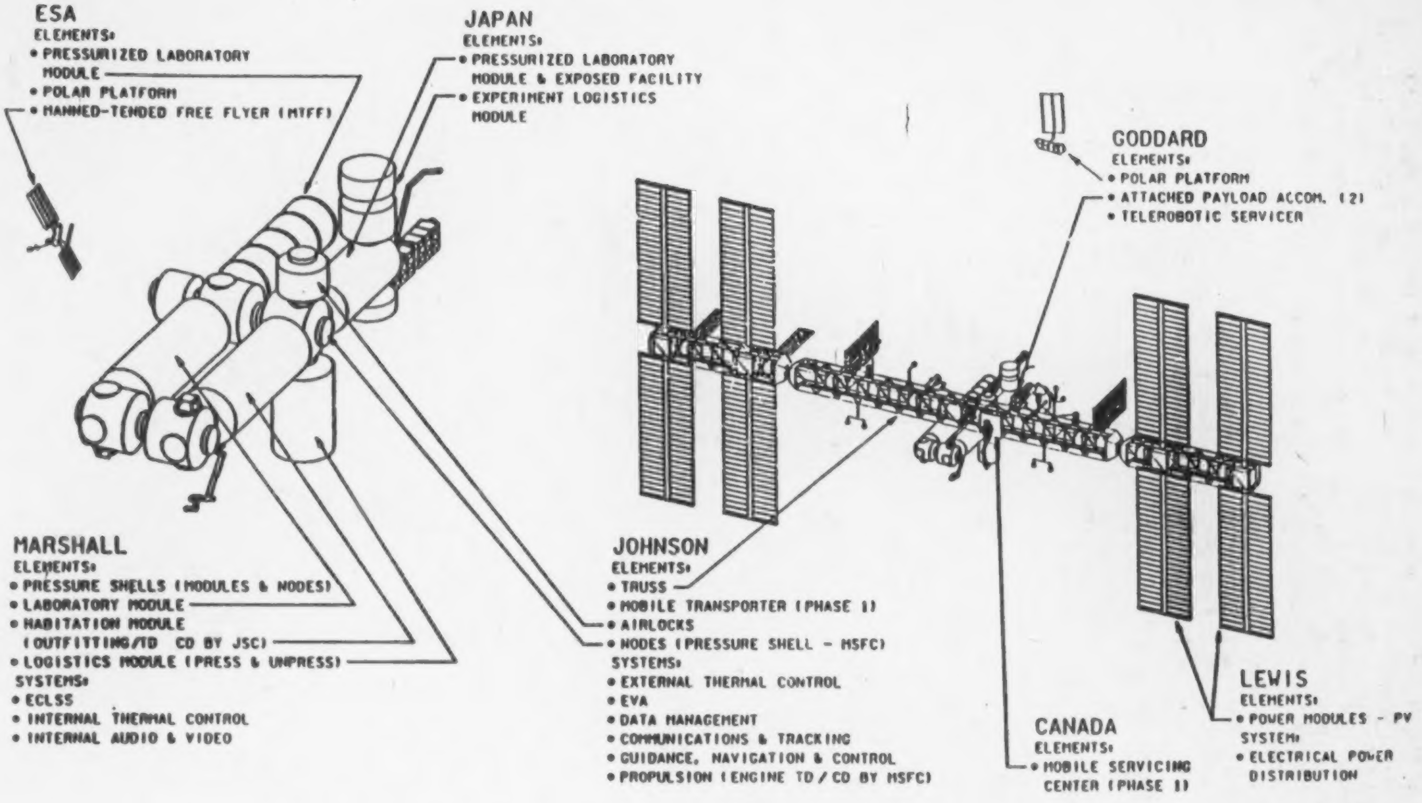

ESA
ELEMENTS:
• PRESSURIZED LABORATORY MODULE
• POLAR PLATFORM
• MANNED-TENDED FREE FLYER (MTFF)
JAPAN
ELEMENTS:
• PRESSURIZED LABORATORY MODULE & EXPOSED FACILITY
• EXPERIMENT LOGISTICS MODULE
GODDARD
ELEMENTS:
• POLAR PLATFORM
• ATTACHED PAYLOAD ACCOM. (2)
• TELEROBOTIC SERVICER
MARSHALL
ELEMENTS:
• PRESSURE SHELLS (MODULES & NODES)
• LABORATORY MODULE
• HABITATION MODULE (OUTFITTING/TD CD BY JSC)
• LOGISTICS MODULE (PRESS & UNPRESS)
SYSTEMS:
• ECLSS
• INTERNAL THERMAL CONTROL
• INTERNAL AUDIO & VIDEO
JOHNSON
ELEMENTS:
• TRUSS
• MOBILE TRANSPORTER (PHASE I)
• AIRLOCKS
• NODES (PRESSURE SHELL - MSFC)
SYSTEMS:
• EXTERNAL THERMAL CONTROL
• EVA
• DATA MANAGEMENT
• COMMUNICATIONS & TRACKING
• GUIDANCE, NAVIGATION & CONTROL
• PROPULSION (ENGINE TD / CD BY MSFC)
CANADA
ELEMENTS:
• MOBILE SERVICING CENTER (PHASE I)
LEWIS
ELEMENTS:
• POWER MODULES - PV SYSTEM:
• ELECTRICAL POWER DISTRIBUTION

Figure A-1. Space Station Plan

the initial phase of a mobile servicing system. The configuration will evolve to accommodate future changes in user requirements. The configuration also includes two unmanned, free-flying Space Station platforms in polar orbit. One will be developed by the United States, the other by ESA. These platforms are an integral part of the Space Station Program and contribute significantly to its versatility and utility.

THE MANNED BASE

The manned base configuration comprises the following components:

- U.S. Laboratory Module
- Columbus Laboratory Module
- Japanese Experiment Module (JEM) Laboratory and Exposed Facility
- Habitation Module
- Mobile Servicing System (MSS)
- Attached Payload Accommodations Equipment (APAE)
- Pressurized Logistics Carrier (PLC)
- Unpressurized Logistics Carrier (ULC)
- Airlock
- Hyperbaric Airlock
- Flight Telerobotic Servicer (FTS)
- Power Modules
- Truss Assembly
- Propulsion Assembly
- Resource Nodes
- Distributed Systems

A description of the manned base components follows.

U.S. Laboratory Module

The U.S. laboratory module is a pressurized cylinder, approximately 45 feet in length and 14 feet in diameter, that will support multidiscipline payloads within a habitable volume. The U.S. laboratory module will be developed to utilize the basic structural design and distributed systems needed to function within all the modules. Principal activities such as basic materials and life science research will be conducted inside the laboratory where low-acceleration levels of long duration, control, and monitoring of experiments and associated apparatus are required. See Figure A-2. The commercial potential of material processes in a very low gravity environment will be investigated in the U.S. laboratory module.

The primary structure consists of the pressure shell, meteoroid shield, NSTS attachment provisions, Space Station attachment provisions, viewports, and grapple fixtures. The secondary structure provides rigidity for attaching equipment to the interior of the module and functional units and racks for support of subsystems and equipment. Standard interface guidelines and resources are provided for both the Space Station and the user. Laboratory operations are managed and controlled in an element control workstation located in the U.S. laboratory module. The U.S. laboratory module also contains provisions for telescience to allow interaction between ground based experimenters and on-orbit experiments.

Functional outfitting equipment will be provided to support on-orbit research and experimental operations. Outfitting equipment will include facilities and apparatus for (1) decontaminating a crewmember should an accident occur involving a toxic substance; (2) monitoring the microgravity environment; (3) preparing and packaging pre-and post-processed samples and specimens; (4) monitoring common fluids and gases routinely required in laboratory operations; (5) handling and storing safely experiment wastes; (6) assaying and characterizing processed samples and specimens; and (7) supporting minor adjustment and repair of equipment.

As depicted in the Figure A-2, user-provided payloads and laboratory support equipment involved in day-to-day operations are located along the port and starboard walls of the U.S. laboratory module. Core subsystems, such as Environmental Control and Life

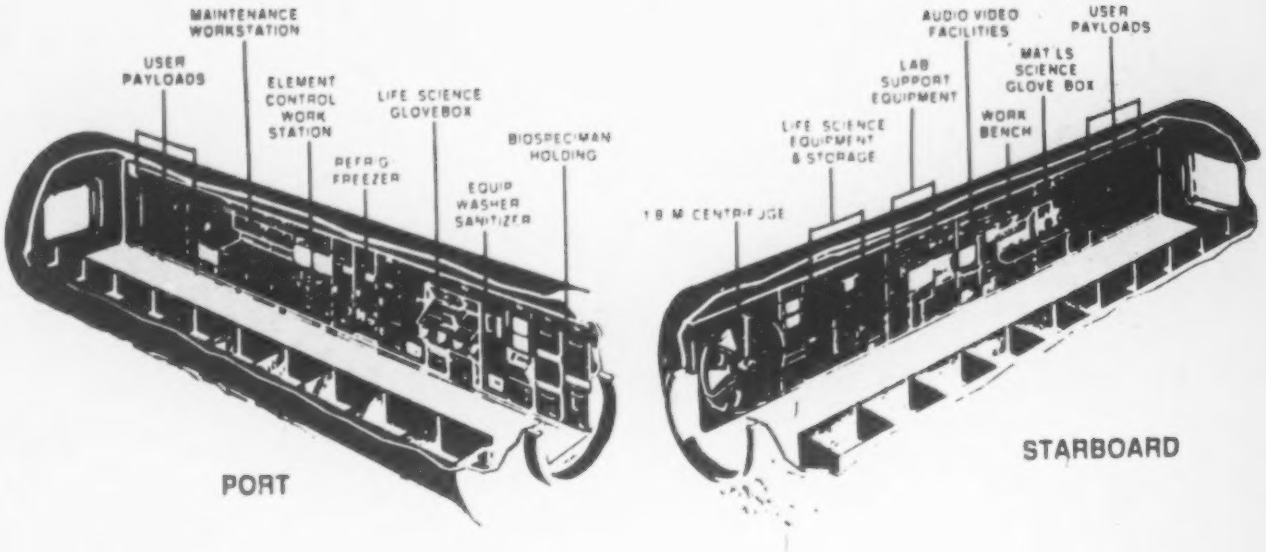

USER PAYLOADS
MAINTENANCE WORKSTATION
ELEMENT CONTROL WORK STATION
REFRIG FREEZER
LIFE SCIENCE GLOVEBOX
EQUIP WASHER SANITIZER
BIOSPECIMAN HOLDING
PORT
1.8 M CENTRIFUGE
LIFE SCIENCE EQUIPMENT & STORAGE
LAB SUPPORT EQUIPMENT
AUDIO VIDEO FACILITIES
WORK BENCH
MAT'LS SCIENCE GLOVE BOX
USER PAYLOADS
STARBOARD

Figure A-2. U.S. Lab Module

Support Systems (ECLSS), outfitting equipment, storage lockers, and equipment requiring infrequent access, are located in the ceiling and floor.

Columbus Laboratory Module

The Columbus laboratory module is a permanently attached, pressurized laboratory module to be built by ESA. The Columbus module is composed of four segments of all-welded primary structure with axially mounted Station-compatible docking ports at each end cone. The internal secondary structure includes removable single and double racks for accommodation of subsystems and payloads. The total volume available for payloads and storage will support approximately 40 single racks. A scientific airlock permits temporary exposure of experiments to vacuum and is also used for the transfer of tools and equipment to support external activities. See Figure A-3.

Japanese Experiment Module (JEM) Laboratory and Exposed Facility

Japan is planning to provide a permanently attached, pressurized laboratory module, an exposed facility, and an Experiment Logistics Module (ELM). See Figure A-4. The exposed facility will be used for scientific observations, Earth observation, communication, and advanced technology development and materials processing for which the unpressurized exposed facility is preferred or required.

The pressurized module structure consists of a cylindrical pressure shell with end-cones, a meteoroid bumper, windows, grapple fixtures, and secondary structure. The module is outfitted with subsystems including electrical power, thermal control, communications, Environmental Control and Life Support (ECLS) and experiment support. The exposed facility consists of an open truss and equipment-attach provisions. The airlock provides access between the pressurized module and the exposed facility and consists of a pressure shell, hatches, a slide table, and controls for pressurization and depressurization.

The ELM provides transportation and storage of logistics items and has the potential to serve as a safe haven for two crewmembers. Consisting of pressurized, exposed, and gas container sections, the ELM will be transported in the NSTS Orbiter payload bay to the Space Station. Following Orbiter docking, the MSS will remove the ELM from the Orbiter payload bay and mate it with the JEM pressurized module.

Habitation Module

The habitation module is an environmentally protected enclosure intended for long-duration crew activity and habitation functions (e.g. eating, sleeping, recreation, relaxation, medical procedures and work activities). The habitation module contains all of the systems necessary for providing a productive environment. Also provided in the habitation module are safe haven emergency supplies for the crew, isolation from other modules, and stowage, equipment, and supplies for daily operations.

The habitation module primary structure is common hardware and provides environmental enclosure, meteoroid protection, viewports, and accommodations for interfaces with NSTS and external elements. The primary structure consists of the pressure shell, meteoroid shield, radiation protection, NSTS attachment provisions, Space Station attachment provisions, viewports, and grapple fixtures. The habitation module secondary structure provides rigidity for attaching equipment to the interior of the module plus interchangeable functional units and racks

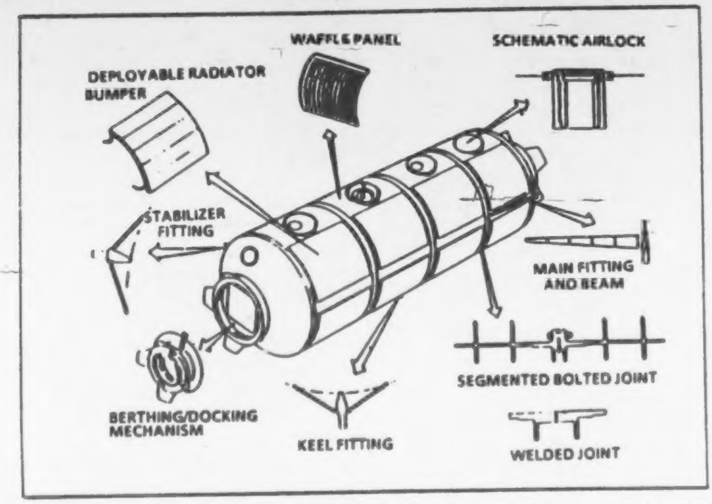

WAFFLE PANEL
SCHEMATIC AIRLOCK
DEPLOYABLE RADIATOR BUMPER
STABILIZER FITTING
MAIN FITTING AND BEAM
SEGMENTED BOLTED JOINT
BERTHING/DOCKING MECHANISM
KEEL FITTING
WELDED JOINT

Figure A-3. External Arrangement Columbus Laboratory Module

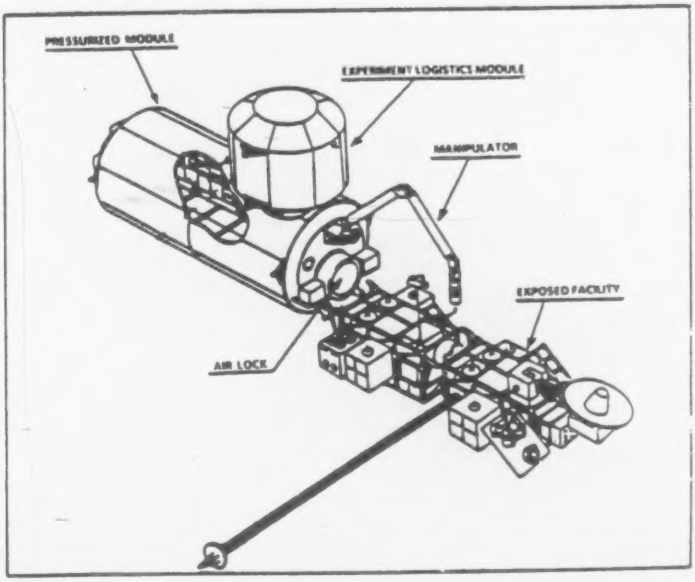

PRESSURIZED MODULE
EXPERIMENT LOGISTICS MODULE
MANIPULATOR
EXPOSED FACILITY
AIR LOCK

Figure A-4. General Arrangement - - Japanese Experiment Module (JEM) for support of subsystems and equipment.

Stowage provisions will be included for habitation module subsystem spares and consumables, allocated Space Station spares and consumables, Orbital Support Equipment (OSE), and subsystem maintenance and trouble shooting equipment. Stowage provisions will also be included for spares, consumables, and tools necessary for functional outfitting.

Mobile Servicing System (MSS)

The Mobile Remote Servicer (MRS), planned by Canada, and the U.S.-provided mobile transporter will make up the Mobile Servicing Centre (MSC). The MSC will be the primary element of the first phase of the Mobile Servicing System. See Figure A-5. In support of construction and assembly functions, the MSS will remove cargo from the Orbiter cargo bay, transport it to the point of construction or assembly, support EVA construction functions with flight crew positioning devices, and provide post-assembly inspection. The MSS will also transport Station elements and payloads to locations on the Space Station as well as provide deployment and retrieval functions. It will also support attached payload servicing (external), Space Station maintenance (external), EVA operations, and safe haven support.

The MSC base provides the primary structural and mechanical system for support and attachment of MSC systems and equipment. The Space Station Remote Manipulator System (RMS) provides the MSC with manipulative, positioning, and handling capability and with the attachment of standard and special end-effectors, can accomplish various tasks including providing utilities to payloads and elements.

The Astronaut Positioning Mechanism (APM) provides crew mobility and is nearly identical to the Space Station RMS. The Special Purpose Dextrous Manipulator (SPDM) is a robotic manipulator which could be used for ORU changeout of Space Station elements and attached payloads and supports other maintenance and servicing functions.

Attached Payload Accommodations Equipment (APAE)

The APAE will provide the accommodations for science, technology, and commercial user payloads external to the pressurized volume of the core Space Station and is attached to the Space Station truss structure. Accommodations will be made for installation and checkout on the Space Station, normal operations, servicing, repair, and removal. For some payloads the APAE can be used during transportation to orbit and return to the ground. The APAE will be modular, allowing various configurations to meet mission needs. This will include carriers designed to accommodate single instruments and those designed to accommodate several small instruments. Pre-integrated instrument pallets as well as instruments requiring gimballed pointing will be accommodated.

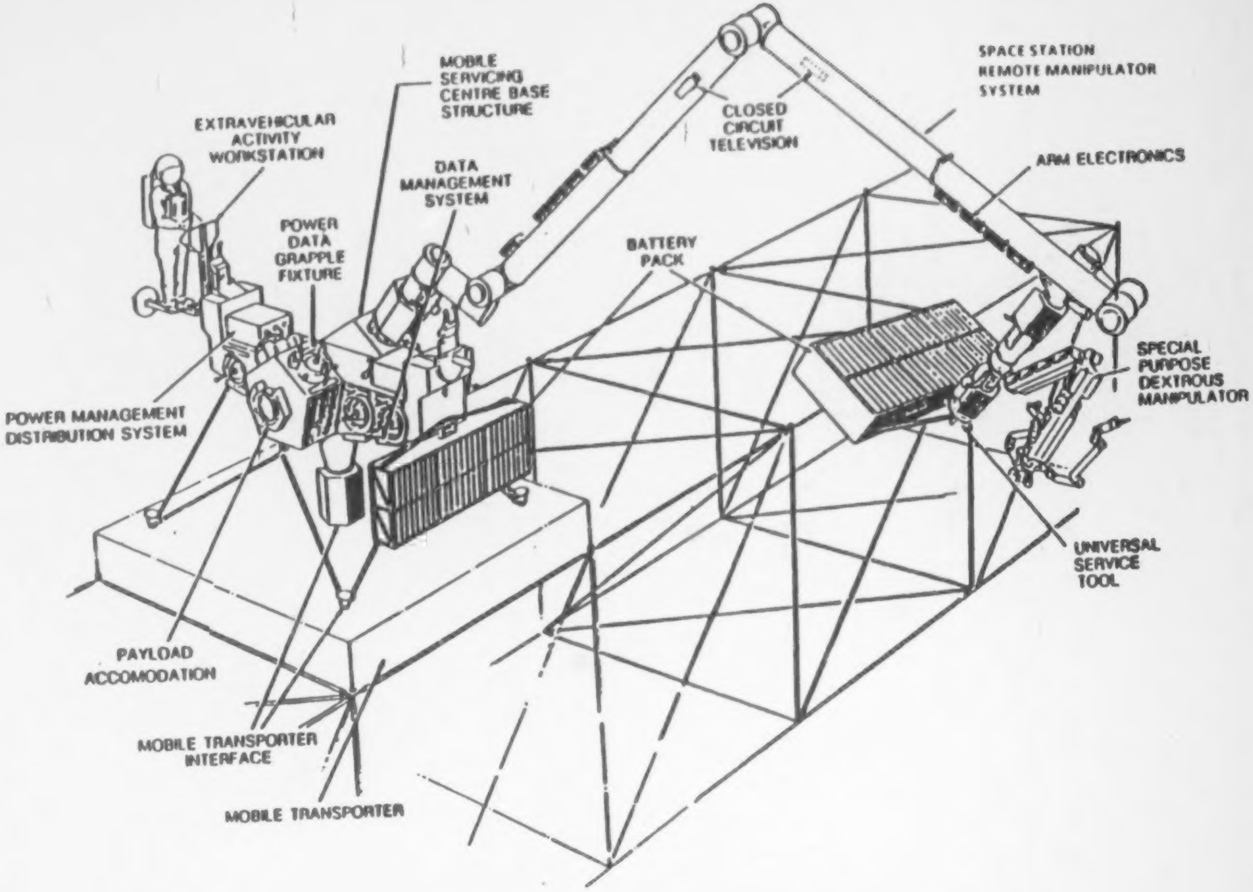

SPACE STATION
REMOTE MANIPULATOR
SYSTEM
CLOSED
CIRCUIT
TELEVISION
MOBILE
SERVICING
CENTRE BASE
STRUCTURE
EXTRAVEHICULAR
ACTIVITY
WORKSTATION
DATA
MANAGEMENT
SYSTEM
ARM ELECTRONICS
POWER
DATA
GRAPPLE
FIXTURE
BATTERY
PACK
SPECIAL
PURPOSE
DEXTROUS
MANIPULATOR
POWER MANAGEMENT
DISTRIBUTION SYSTEM
UNIVERSAL
SERVICE
TOOL
PAYLOAD
ACCOMODATION
MOBILE TRANSPORTER
INTERFACE
MOBILE TRANSPORTER

Figure A-5. Mobile Servicing Center

Pressurized Logistics Carrier (PLC)

The PLC transports equipment and fluids between the ground and the Space Station and will be carried in the Orbiter payload bay.

The PLC uses structures common to other Station modules as shown in Figure A-6. The primary structure consists of a cylindrical pressure shell with conical ends and provides a meteoroid shield, NSTS attachments, and Space Station attachments. The secondary structure provides support for the distributed subsystems and utilities; secured stowage; and containment facilities for interchangeable racks containing spare parts, ORUs, experiment parts, consumables, and other storable items.

Unpressurized Logistics Carrier (ULC)

The ULC transports equipment and fluids to the Space Station and returns items to the ground. The cargo transported does not require a pressurized environment and is used external to the pressurized volume. The types of cargo accommodated by the ULC include ORUs for the Space Station, station payloads and experiments, and fluids.

The ULC cylindrical structure provides support for racks, tanks, and sub-pallets; grapple fixtures and NSTS attachment fittings; and hard points for non-rack mounted hardware and subsystem equipment. See Figure A-7.

Airlock

The airlock provides the capability to transfer EVA-suited crewmembers and equipment between the pressurized and unpressurized areas of the Space Station. Storage and servicing of EVA system equipment is also provided by the airlock.

The distributed systems and utilities required to support a manned environment are an integral part of the airlock. The airlock structure provides the functions of a pressure vessel, radiation and meteoroid and debris protection, hatches, and support for the installed equipment. Openings for egress and ingress and the capability to move small items between pressurized and unpressurized areas without depressurizing the entire airlock are provided.

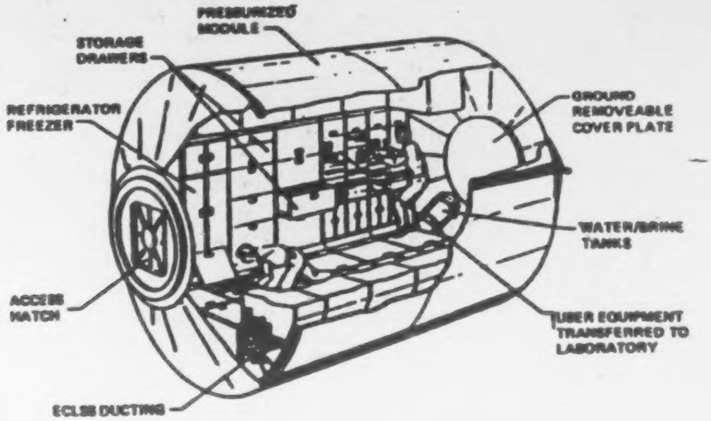

PRESSURIZED MODULE
STORAGE DRAWERS
REFRIGERATOR FREEZER
GROUND REMOVEABLE COVER PLATE
WATER/BRINE TANKS
ACCESS HATCH
USER EQUIPMENT TRANSFERRED TO LABORATORY
ECLSS DUCTING

Figure A-6. Pressurized Logistics Carrier

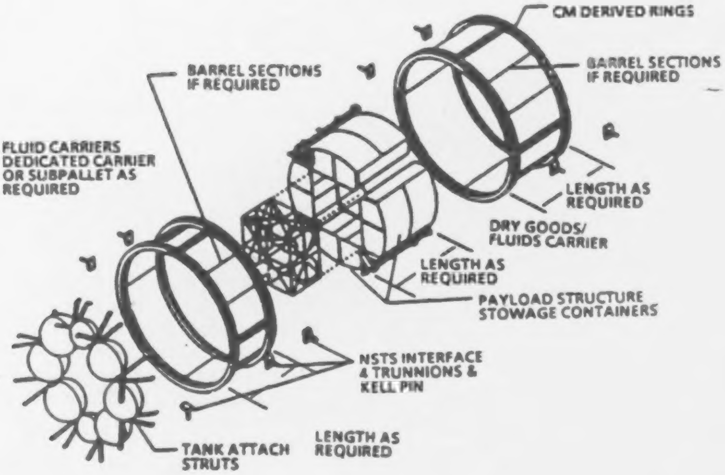

CM DERIVED RINGS
BARREL SECTIONS IF REQUIRED
BARREL SECTIONS IF REQUIRED
FLUID CARRIERS DEDICATED CARRIER OR SUBPALLET AS REQUIRED
LENGTH AS REQUIRED
DRY GOODS/ FLUIDS CARRIER
LENGTH AS REQUIRED
PAYLOAD STRUCTURE STOWAGE CONTAINERS
NSTS INTERFACE 4 TRUNNIONS & KELL PIN
TANK ATTACH STRUTS
LENGTH AS REQUIRED

Figure A-7. Unpressurized Logistics Carrier

Hyperbaric Airlock

The hyperbaric airlock is capable of functioning at higher pressures in the event that a crewmember requires medical attention. The hyperbaric airlock has the capability to pass items to and from the Space Station without losing pressure during hyperbaric operations. See Figure A-8.

Flight Telerobotic Servicer (FTS)

The FTS onboard the Space Station increases crew safety and productivity by reducing EVA time, using robotics for hazardous tasks, and freeing crewmembers from routine tasks. In the development of A&R technologies, the FTS will play a key role.

Proposed initial capabilities of the FTS include installation and removal of truss members, installation of fixtures on the truss, changeout of Space Station ORUs, mating the Space Station thermal utility connectors, and performing inspection tasks.

The FTS will be operable by using both direct manipulator control and command sequences. The FTS must be operable from different workstations as the Space Station develops. At the Space Station FEL, it must be operated from the NSTS. Later it must be able to be controlled from inside the Space Station.

The FTS element has been divided into eight separate subsystems each having unique functions. The Structures and Mechanisms subsystem provides hardware and software interfaces for attaching the FTS to a transport device, worksite, or storage area as well as for being grappled and for power and data connections. The telerobot structure provides strength, and houses the components and accommodations for other subsystems. The Telerobot Control Subsystem provides control of the robot and its manipulators during all mission operations. The Telerobot Safing Subsystem provides for safe and orderly telerobot operation and shutdown upon failure detection. The Workstation Subsystem provides the man-machine interfaces for both teleoperation and autonomous control of FTS operations by an operator. It includes all the FTS unique hardware and software necessary for sensor processing and robot control. Other subsystems provide power, thermal control, communications, and data management.

The modular structure of the FTS hardware and software will ensure serviceability. Its flexible configuration will facilitate evolutionary and technological upgrades to the Space Station.

Power Modules

Each power module is capable of collecting solar energy and converting it to electrical energy. Power modules can also store energy for orbital operations, transfer electrical power to Station power-using elements, and control the operation of the Electric Power System (EPS) equipment housed in the power module. The total average power will be 75 kW.

A general representation of a photovoltaic power module is shown in Figure A-9. The primary structural component will be struts similar to those which make up the truss element. Secondary structure will be provided to support and attach system and element-supplied equipment. Primary and secondary structures will be used to derive node spacing identical to the main truss. Power distribution and control equipment will be provided to allow powering and control of individual loads within the element.

Truss Assembly

The truss assembly provides the structure for integration and installation of

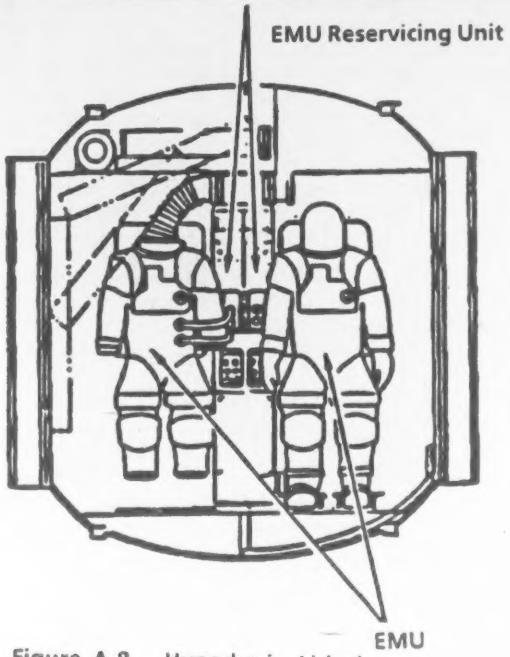

EMU Reservicing Unit
EMU

Figure A-8. Hyperbaric Airlock

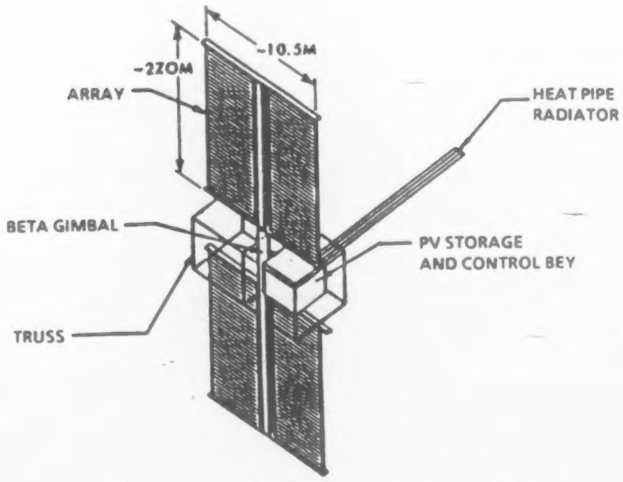

-220M
-10.5M
ARRAY
HEAT PIPE RADIATOR
BETA GIMBAL
PV STORAGE AND CONTROL BEY
TRUSS

Figure A-9. Photovoltaic Power Module

the distributed systems and elements. The truss element includes the core Station integrated truss structure, all distributed systems and element-supplied equipment within the truss structure, and provisions for mounting and attaching other elements. The truss also provides corridors for crew and equipment movement, utility distribution networks, and solar array pointing capability with the alpha joint and drive mechanism.

The truss structure is an in-space erectable structure composed of longerons, battens, and diagonal struts. These members are attached to corner fittings forming a beam truss of sequential cubic bays measuring 5 meters from strut centerline to centerline. The truss provides structural stiffness and dimensional stability for the Station. Fittings also provide attachments for mobile interfaces.

EVA truss equipment is provided to assist a crewmember when moving about the structure. Unpressurized logistics carriers pallets are interfaces for attaching the logistics carriers to the truss. Resource pallets are common interfacing hardware for attaching external Station systems to the truss and utility distribution system.

All subsystem distribution lines (thermal, power, fluids, and data management) are housed in the utility distribution trays. These trays facilitate on-orbit assembly of the utility distribution system and provide protection from natural and induced environments. External lighting provides visual monitoring of rendezvous and other external activities.

Propulsion Assembly

The propulsion assembly provides three-axis thrust for attitude stabilization and reorientation control should disturbances exceed the primary momentum system capability. The assembly provides thrust to compensate for atmospheric drag and to execute collision avoidance, and it contains propellant reserve.

Propulsive thrust is achieved from two sources. The recombination of oxygen and hydrogen extracted from onboard water by electrolysis provides the primary attitude control thrust. Waste products are used as fuel for low-thrust resistojets to maintain altitude.

Resource Nodes

The resource node is a pressurized and environmentally protected enclosure intended for crew activity such as Space Station command, control, and operation. Distributed systems and related controls are housed in the nodes and provide module pattern growth. Each node will be outfitted for specialized functions. See Figure A-10.

Node 1 is the unmanned spacecraft control center. Node 1 provides a pressurized passageway to and from the modules, hyperbaric airlock, and logistics elements and provides berthing for the hyperbaric airlock, pressurized modules, and logistic module. This node provides Space Station control of unmanned flights as well as man-tended operations. Node 1 contains major components of the propulsion subsystem and has direct interface with the Columbus laboratory module provided by ESA.

Node 2 is the man-tended command and control station. Node 2 provides a pressurized passageway to and from the modules, airlock, and logistics elements and provides berthing for the airlock and pressurized modules. Node 2 contains the airlock control station and has direct interface with the Japanese Experiment Module (JEM) laboratory.

Node 3 is the primary command and control station for the Permanently Manned Configuration (PMC). It provides a pressurized passageway to and from the modules and NSTS, berthing for the NSTS, and attachment capability for the cupola. This node provides the Space Station primary command and control workstations and contains distributed systems of the Space Station utility systems, mechanisms for the module-to-node berthing and module pattern growth, a proximity operations control station, pressurized attached payload accommodations equipment port, and a backup Mobile Servicing System (MSS) control station.

Node 4 is the proximity operations station, prime MSS control station, and reserve volume. It provides a pressurized passageway to and from the modules and the NSTS, berthing for the NSTS, attachment capability for the cupola and pressurized modules, and module pattern growth. This node provides the Space Station prime MSS command and control workstations and contains utility systems, mechanisms for the module-to-node berthing and module pattern growth, and cupolas for the proximity operations control station.

The node primary structure provides the pressurized shell including the frame and skin. The secondary structure provides interfaces for external environmental protection, rigidity for attaching equipment and utilities to the interior of the module, and attachment points for hardware. The function of berthing and attaching elements to the node, truss and cupola, the cupola interface, and the pressurized payload accommodation interface, docking equipment, and hatches is also provided by the secondary node structure. Cupolas are attached to node ports to allow direct viewing of external activities.

DISTRIBUTED SYSTEMS

There are a number of subsystems that provide services and capabilities that are located in more than one module or element and have to transit the boundaries and interfaces between modules and elements. These distributed systems provide essential functions and are listed below.

-- Electric Power System (EPS)
-- Data Management Systems (DMS)
-- Thermal Control System (TCS)
-- Communications and Tracking (C&T) System
-- Guidance, Navigation and Control (GN&C) System
-- Extravehicular Activity (EVA) System
-- Environmental Control and Life Support System (ECLSS)
-- Man Systems
-- Fluid Management System (FMS)

A description of the Space Station distributed systems follows.

Electric Power System (EPS)

The end-to-end EPS architecture for the Space Station begins with the collection of solar energy and extends to every place that electric power is consumed. The EPS includes load converters required to convert the distributed power to a different type for specific local use and components beyond those converters which are required to distribute power to the location of its use.

The EPS configuration consists of two photovoltaic modules on both sides with each module having two solar array wings. The continuous average power level capability of the EPS at this phase of the Program is 75 kW.

Power generation, energy storage, system control, and some distribution equipment are located in the photovoltaic modules.

The power generation equipment includes source power converters to convert the output of the basic generation system to the utility grade 20 kHz, single phase, alternating current power which is distributed throughout the Space Station. The outputs of these converters are synchronized and locked to a common frequency to allow paralleling. Energy storage is accomplished by means of nickel hydrogen batteries. Appropriate power system controls are included in each of the modules to regulate the generation, storage, and converter functions.

The overall distribution subsystem includes all equipment necessary to process, control, and distribute power from source to load interfaces. These interfaces include housekeeping loads for the overall Station operation, attached payloads, and module payloads.

The electrical primary distribution architecture for the Station manned core is implemented as a modified dual-ring bus system which provides utility power to external load areas. Each of the four modules will be supplied through one or more nodes. Transformers are used at the node penetrations to provide isolation for the single point ground system and to reduce voltage to the standard value supplied. See Figure A-11.

Data Management System (DMS)

The DMS is an ensemble of common hardware and software including a family of standard processors, network devices, mass memory storage units, and a time and frequency distribution system. The DMS also controls and monitors media for crew and experimenters. These common resources are utilized by all Space Station systems to satisfy their respective data and information management responsibilities.

The common DMS resources are configured to provide and support semi-autonomous operations of distributed systems and payloads. The DMS utilizes internationally agreed standards for Open Systems Interconnect for interprocessor network communications. The network, in conjunction with standard user interfaces, permits remote and distributed control and monitoring of Space Station activity. DMS software services include user functions such as onboard data base management operations, fault and redundancy management, vehicle and systems configuration management, and services for vehicle operations such as systems initialization, caution, and warning. In addition, DMS architecture for an automated Operations Management System (OMS) encompasses onboard applications software for crew activities planning, command and resources management, and onboard integration and verification testing.

Thermal Control System (TCS)

The TCS for the core station essentially consists of a central Active Thermal Control System (ATCS) which collects, transports, and rejects waste heat for all parts of the Space Station. The heat is collected from Space Station systems or payloads through a heat exchanger to a thermal bus. There are two thermal buses interconnected by a heat exchanger. The external bus uses ammonia, and the internal bus uses water as working fluids. Heat is transferred by the thermal bus to radiators where heat is rejected.

Surface coatings and thermal blankets are used to provide thermal protection and heat balance between sensitive components and the environment. Electric heaters or waste heat is to be used for precise temperature control of critical items.

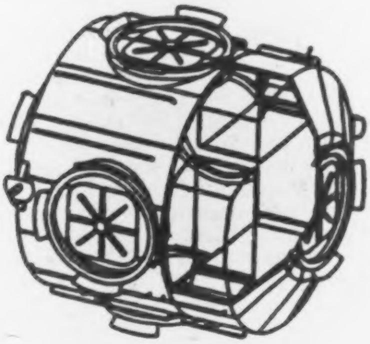


Figure A-10. Resource Node

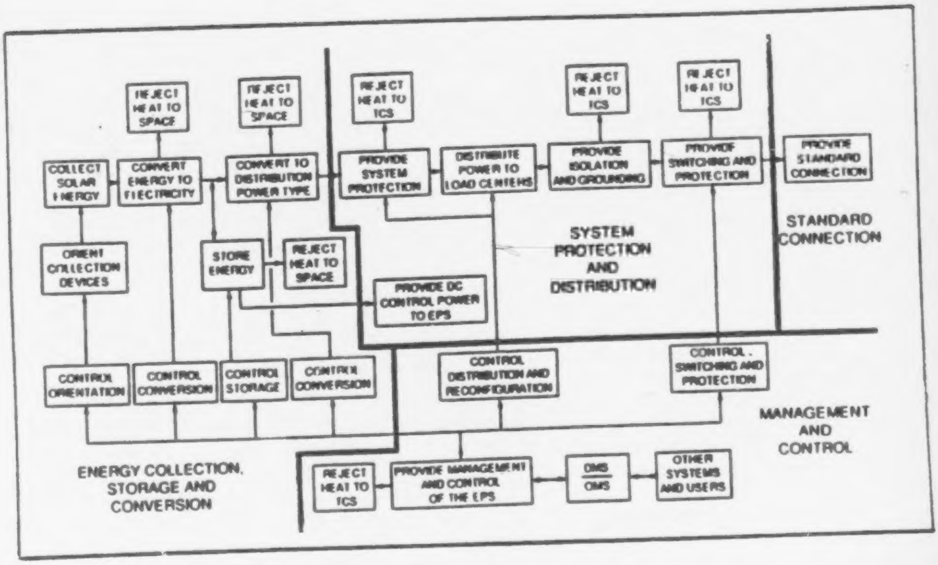

REJECT HEAT TO SPACE
REJECT HEAT TO SPACE
REJECT HEAT TO ICS
REJECT HEAT TO ICS
REJECT HEAT TO ICS
COLLECT SOLAR ENERGY
CONVERT ENERGY TO ELECTRICITY
CONVERT TO DISTRIBUTION POWER TYPE
PROVIDE SYSTEM PROTECTION
DISTRIBUTE POWER TO LOAD CENTERS
PROVIDE ISOLATION AND GROUNDING
PROVIDE SWITCHING AND PROTECTION
PROVIDE STANDARD CONNECTION
STANDARD CONNECTION
ORIENT COLLECTION DEVICES
STORE ENERGY
REJECT HEAT TO SPACE
PROVIDE DC CONTROL POWER TO EPS
SYSTEM PROTECTION AND DISTRIBUTION
CONTROL ORIENTATION
CONTROL CONVERSION
CONTROL STORAGE
CONTROL CONVERSION
CONTROL DISTRIBUTION AND RECONFIGURATION
CONTROL, SWITCHING AND PROTECTION
MANAGEMENT AND CONTROL
ENERGY COLLECTION, STORAGE AND CONVERSION
REJECT HEAT TO ICS
PROVIDE MANAGEMENT AND CONTROL OF THE EPS
DMS / OMS
OTHER SYSTEMS AND USERS

Figure A-11. Electrical Power System

Monitoring, control, data acquisition, and Caution and Warning (C&W) functions interface with the DMS. See Figure A-12.

Communications and Tracking (C&T) System

The C&T System provides all required communications services for the Space Station within and between pressurized elements, between the manned Station and all external space elements, and between the Station and ground based elements. These services include necessary Radio Frequency (RF) data transmissions; video generation, processing, distribution, and control; audio generation, processing, distribution, and control; and all communication services required by the Guidance, Navigation, and Control (GN&C) System. Also included in the system are the necessary interfaces to the DMS and the components required to furnish the built-in management, administration, and operation of the elements of the system.

Development responsibility for the system has been partitioned into two components: the hardware and communication functions necessary for external operations (EVA, outside monitoring, navigation, Shuttle docking, etc.) and those functions necessary for all internal communications. Responsibility for the external component is assigned to JSC to provide a close interface with the assembly and EVA tasks while development for the internal component is assigned to MSFC since this component is an integral part of the development and functional performance of the module systems.

When full operations are achieved, space-to-ground communications will be via a digital format radio system which communicates to ground stations through the TDRSS using a steerable, parabolic antenna. S-Band equipment will provide an initial Space Station - to - ground communications capability through TDRSS at low data rates and will thereafter be available for use as a contingency link.

Primary space-to-space communications will be accomplished through a multi-access system which will be capable of simultaneous two-way communications to support EVA operations and communications to other space vehicles which have compatible systems. These links will be capable of carrying voice, video, and data which can then be distributed, as appropriate, to other Space Station subsystems upon reception. In addition, the C&T system will receive timing signals from the Global Positioning System (GPS) constellation and generate the Space Station orbital data for navigation requirements. The GPS data will also be utilized to generate the Station timing reference.

The internal video subsystem will provide a comprehensive closed-circuit television capability within the Space Station along with a full range of media-standard processing capabilities. These video processing capabilities include video storage, retrieval, compression, special effects, graphics, and digital processing (where appropriate). The subsystem will allow special area monitoring, will support conferencing between crew locations and between the crew and ground, and will accommodate high resolution cameras where required. The system will provide its own built-in control for test and reconfiguration as commanded.

The internal audio subsystem will be similar to a standard telephone system with private and/or conferencing capability between the internal crew, EVA crew, the crew of other manned vehicles, and compatible ground systems. The system will provide all standard ancillary audio services such as recording, playback, voice recognition, voice synthesis, message routing, built-in test, and commanded reconfiguration. In addition, this system will provide the capability to annunciate C&W to the crew, as appropriate.

Guidance, Navigation and Control (GN&C) System

GN&C provides core system control and traffic management functions. The core system provides attitude and orbital maintenance, supports the pointing of power system and thermal radiators, accomplishes periodic reboost maneuvers, and provides Station state and attitude information to other systems and users. The core GN&C will provide drive electronics at solar array alpha joints and thermal radiators.

Traffic management provides for controlling incoming, outgoing, and station-keeping traffic within the Command and Control Zone (CCZ) of the Station; controlling docking and berthing operations; monitoring trajectories of vehicles and objects that may intersect the orbit of the Station; predicting potential collisions; and supporting flight planning.

The core GN&C system consists of inertial sensor assemblies, star trackers, and control moment gyros located on the attitude control assembly of the transverse boom and standard data processors located in resource nodes 1 and 2. The GN&C System will interface directly with the propulsion system thrusters for reboost and backup attitude control. Orbital state data are provided by the GPS via an interface with the C&T System. This configuration provides a GN&C capability throughout the assembly sequence.

Extravehicular Activity (EVA) System

The EVA System provides the functions necessary for Space Station crewmembers to perform routine tasks in the unpressurized environment on and about the Space Station as well as operations within unpressurized Space Station modules. The system will support assembly, maintenance, repair, inspection, and servicing of Station and user systems.

The EVA system consists of the the Space Station Extravehicular Mobility Unit (EMU); EVA crew and equipment mobility aids; EVA crew rescue and equipment retrieval provisions; EMU contamination detection and decontamination unit; and EVA lighting, generic tools, and miscellaneous support equipment.

One of the space suit designs under study would contain mobility joint systems, a rapid on/off entry closure system, an extravehicular hazards protection coverlayer, and provisions for quick, on-orbit change of space suit size and hardware components.

The portable life support system contains regenerable, non-venting heat rejection and carbon dioxide absorber systems as well as an automatic temperature control system for regulation of flow conditions to the Liquid Cooling Ventilation Garment (LCVG) worn by crewmembers for removal of metabolic heat generated during EVA. The portable life support system also contains provisions for on-orbit servicing and automatic checkout.

Environmental Control and Life Support System (ECLSS)

The ECLSS provides a habitable environment for crew and biological experiment specimens. The system maintains cabin atmosphere temperature, humidity, pressure, and composition. It provides potable and hygiene water, processes and stores biological wastes, and supports crew EVAs. The ECLSS provides air cooling of equipment and detection and suppression of fires.

The U.S. ECLSS hardware is distributed throughout pressurized U.S. elements and operates continuously. Life critical hardware is located in each of the two U.S. modules to provide redundancy. Each life critical subsystem is sized to support a crew of 8 for 45 days under emergency conditions. The atmosphere control and supply hardware required for repressurization is located in each U.S. element (as is fire detection and suppression equipment). The ECLSS is composed of the following subsystems: temperature and humidity control, atmosphere control and supply, atmosphere revitalization, fire detection and suppression, water recovery and management, waste management, and EVA support.

To ensure commonality, ECLSS controllers are common with the DMS processors and are part of the DMS architecture. The controllers ensure safe, efficient operations and communicate ECLS status to crewmembers via the DMS. All instrumentation required for control and monitoring of the ECLSS and interfacing with the C&W system is part of the ECLSS architecture. See Figure A-13.

Man Systems

Man Systems is a term used to describe a distributed system for crew habitation, equipment, and other necessities for a productive and sustained working environment. Included in Man Systems are subsystems that support crew safety, health, hygiene, nutrition, Station operations, housekeeping, and stowage. Man Systems hardware and functions are allocated to all pressurized volumes and interact with many Space Station systems and subsystems. A major portion of these accommodations is in the habitation module. The Man Systems principal interface is with the Station DMS. The electronic core consists of a Multipurpose Applications Console (MAC) with displays and controls, audio and video interfaces, resident firmware, and overall software. Areas involving Man Systems and crew support shall be designed to facilitate human productivity and habitability. Crew interfaces and associated equipment will be designed for ease of maintenance, housekeeping, contamination control, and crew safety. In particular, it is vital to Man Systems to have in place standardized emergency controls and procedures. See Figure A-14.

Fluid Management System (FMS)

The FMS encompasses the distributed fluid systems of the Space Station Program. The distributed fluid systems of the FMS generally consist of two different types, supply and disposal. The first combines the requirements of several users of the same fluid into a centralized resupply, storage, and distribution system which provides the fluid to the users at a specified interface condition. The second combines common requirements of several users for vacuum and fluid disposal into an integrated system. Fluid systems include nitrogen, water, and waste fluids. See Figure A-15.

PLATFORMS

The Platforms are the orbiting, unmanned elements of the Space Station system designed to support long-term, autonomous, commercial, scientific, and technological ventures and investigations. The Program includes two polar platforms, one provided by the United States and one provided by ESA.

U.S. Polar Orbiting Platform (POP)

The U.S. polar platform will carry instruments that interface directly with the platform. Operating in a near-polar orbit, the platform will support the following types of missions: Earth biological and geological observations, oceanographic and ice activity studies,

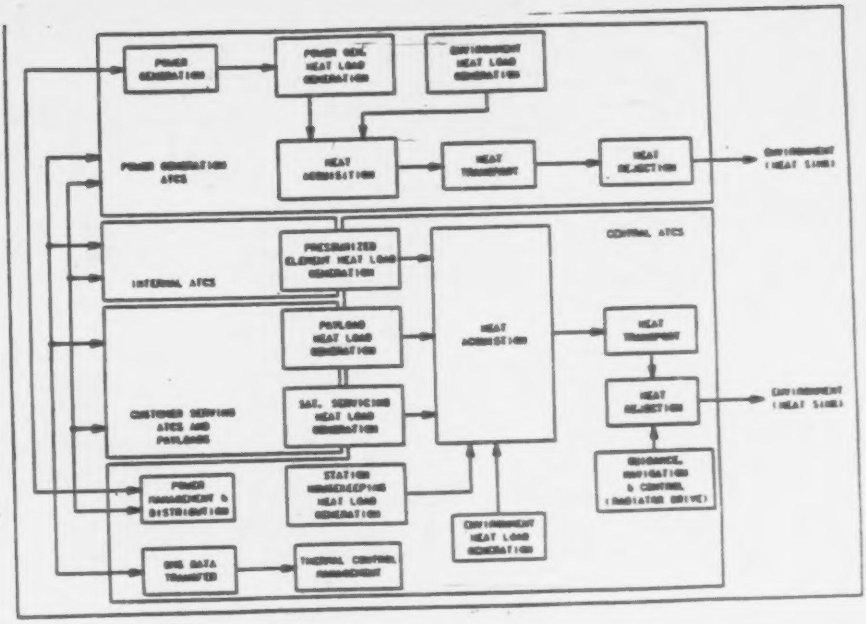

POWER GENERATION
POWER GEN. HEAT LOAD GENERATION
ENVIRONMENT HEAT LOAD GENERATION
POWER GENERATION ATCS
HEAT ACQUISITION
HEAT TRANSPORT
HEAT REJECTION
ENVIRONMENT (HEAT SINK)
CENTRAL ATCS
INTERNAL ATCS
PRESSURIZED ELEMENT HEAT LOAD GENERATION
PAYLOAD HEAT LOAD GENERATION
HEAT ACQUISITION
HEAT TRANSPORT
HEAT REJECTION
ENVIRONMENT (HEAT SINK)
CUSTOMER SERVING ATCS AND PAYLOADS
SAT. SERVICING HEAT LOAD GENERATION
POWER MANAGEMENT & DISTRIBUTION
STATION HOUSEKEEPING HEAT LOAD GENERATION
GUIDANCE, NAVIGATION & CONTROL (RADIATOR DRIVE)
ENVIRONMENT HEAT LOAD GENERATION
BUS DATA TRANSFER
THERMAL CONTROL MANAGEMENT

Figure A-12. Active Thermal Control System

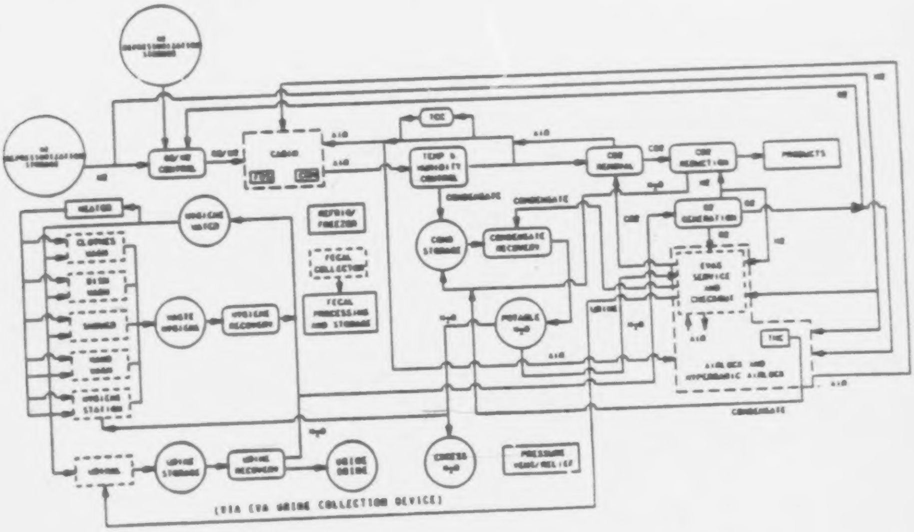

CABIN
AIR
TCC
TEMP & HUMIDITY CONTROL
CO2 REMOVAL
CO2
CO2 REDUCTION
PRODUCTS
CONDENSATE
HEATER
HYGIENE WATER
REFRIG/ FREEZER
CLOTHES WASH
DISH WASH
SHOWER
HAND WASH
HYGIENE STATION
FECAL COLLECTOR
FECAL PROCESSING AND STORAGE
WASTE HYGIENE
HYGIENE RECOVERY
COND STORAGE
CONDENSATE RECOVERY
O2 GENERATION
O2
H2
EVAS SERVICE AND CHECKOUT
POTABLE H2O
H2O
URINE
TCC
AIRLOCKS AND HYPERBARIC AIRLOCKS
URINAL
URINE STORAGE
URINE RECOVERY
URINE BRINE
EXCESS H2O
PRESSURE VENT/RELIEF
(VIA EVA URINE COLLECTION DEVICE)

Figure A-13. Space Station ECLSS Overview

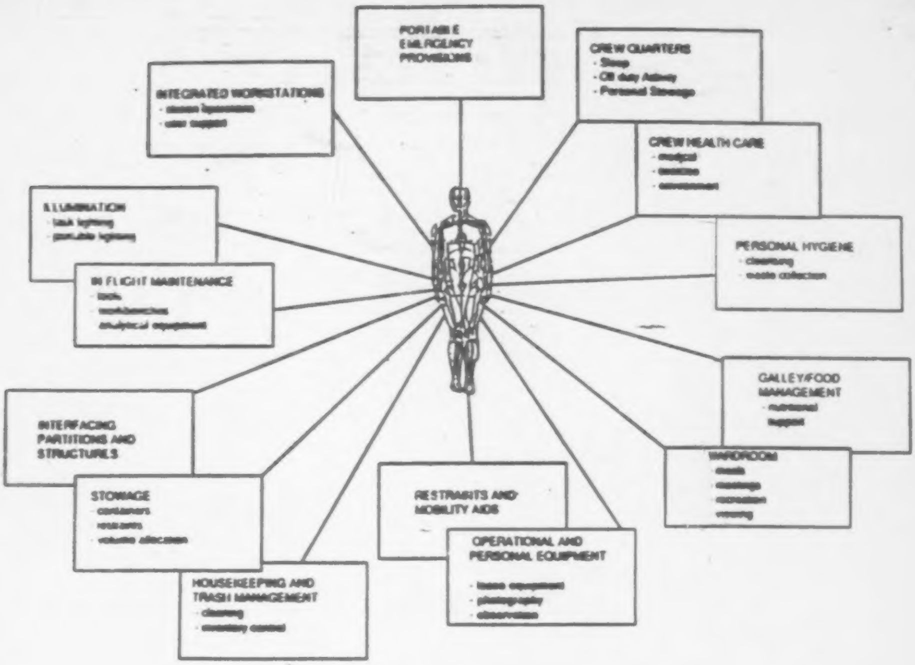

PORTABLE
EMERGENCY
PROVISIONS
INTEGRATED WORKSTATIONS
- user support
CREW QUARTERS
- Sleep
- Off duty Activity
- Personal Stowage
CREW HEALTH CARE
- medical
- exercise
ILLUMINATION
- task lighting
- portable lighting
PERSONAL HYGIENE
- cleansing
- waste collection
IN FLIGHT MAINTENANCE
- tools
- workbenches
analytical equipment
GALLEY/FOOD
MANAGEMENT
- nutritional
support
INTERFACING
PARTITIONS AND
STRUCTURES
WARDROOM
- meals
- meetings
- recreation
- viewing
STOWAGE
- containers
- restraints
- volume allocation
RESTRAINTS AND
MOBILITY AIDS
OPERATIONAL AND
PERSONAL EQUIPMENT
- photography
- observation
HOUSEKEEPING AND
TRASH MANAGEMENT
- cleaning
- inventory control

Figure A-14. Man Systems

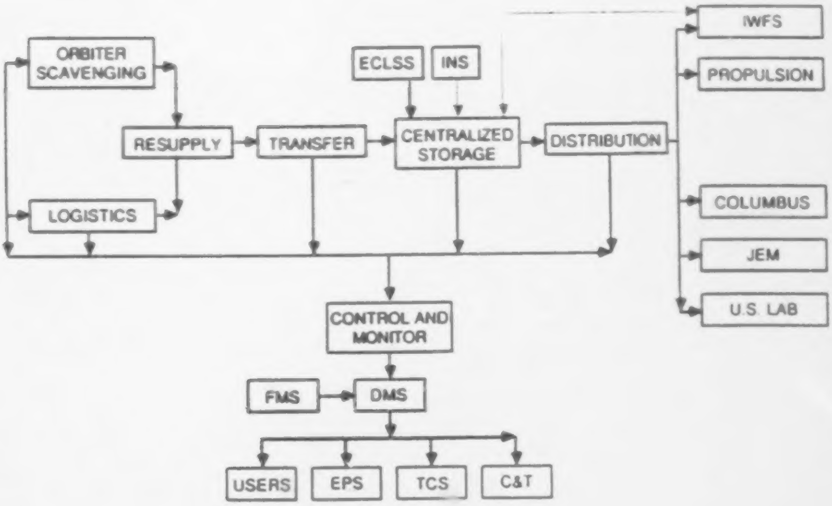

IWFS
ORBITER
SCAVENGING
ECLSS
INS
PROPULSION
RESUPPLY
TRANSFER
CENTRALIZED
STORAGE
DISTRIBUTION
LOGISTICS
COLUMBUS
JEM
U.S. LAB
CONTROL AND
MONITOR
FMS
DMS
USERS
EPS
TCS
C&T

Figure A-15. Integrated Water System (IWS)

Earth lower-and upper-atmospheric monitoring and research, solar observations, and plasma physics measurements.

The platform major modules are the primary carrier, the supplemental carrier, and the propulsion module. Platform resources are supplied by modular ORUs. ORUs are both standard, those which package resources into standard-sized units and use a standard interface connector, and nonstandard, those which require unique packaging and mounting (e.g., solar arrays, antennas, magnetic torquer bars).

The primary and supplemental carriers will accommodate both resource ORUs and payloads. The primary carrier, however, may contain key resources not supported by the supplemental carriers. The primary carrier will contain all of the power generation capability (i.e., solar arrays and drives), the standard C&T resources, and the interface to the propulsion module. The supplemental carrier, in addition to the payloads it carries, will bring the additional resources such as battery and data storage ORUs needed to support an increased complement of users. Consequently, the EPS and the DMS will be distributed across the carriers to supply the entire platform resource needs. The thermal system, however, will be a hybrid system with each carrier being thermally self-sufficient so that thermal fluid transfer across carrier interfaces will not be required.

The primary and supplementary carrier assemblies use the same modular structural components. This allows variable module lengths to accommodate the requirements of a particular complement of payloads and resource ORUs. The primary and supplementary carriers will provide a grid pattern of standardized resource interface connectors for payloads. The same standard interface connectors will be used for ORUs. Resources include structural, power, thermal, and data interfaces.

Payloads can be attached to the grid locations individually, or an assemblage of smaller payloads can share a single grid interface by being integrated onto a common interface plate. See Figure A-16.

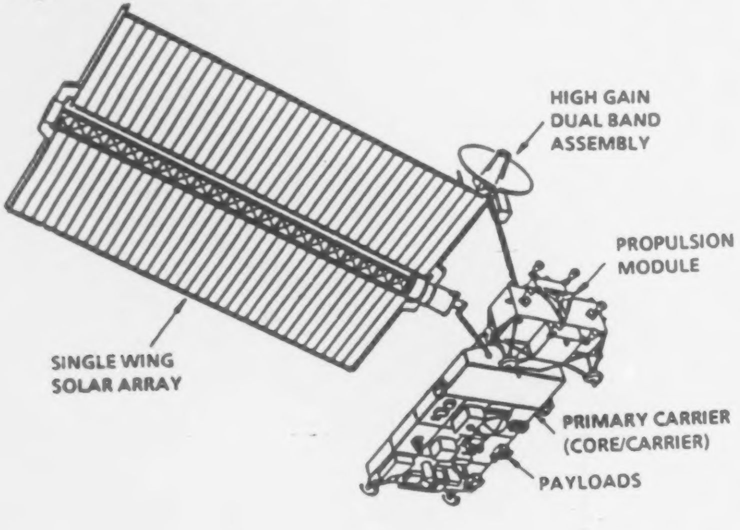


Figure A-16. United States Polar Platform

ESA Polar Platform

The ESA Polar Platform is an unmanned free-flyer providing standard resources (power, pointing, communications, etc.) primarily to Earth observation payloads requiring a low-Earth, Sun synchronous orbit. See Figure A-17.

The platform reference configuration includes a propulsion module, a utilities and payloads structure, a two-wing solar array, nickel-hydrogen batteries and radiators, and communications and tracking subsystems. Current studies include backup launch vehicle alternatives, servicing scenario options, and a review of commonality between the platform utilities module and the Man-Tended Free Flyer (MTFF) Resource Module.

ESA Man-Tended Free Flyer (MTFF)

The MTFF is an ESA-built, unmanned, pressurized laboratory for long duration microgravity applications in the fields of fluid physics, life, and material sciences. It is designed for launch by an Ariane 5 into a Space Station compatible orbit with periodic servicing at the Station. The initial Station servicing will not occur earlier than one year following the completion of on-orbit assembly.

The MTFF consists of a two-segment Pressurized Module (PM) supported by an externally attached Resource Module (RM). MTFF payloads are carried within the two cylindrical segments of the PM which are identical to those of the Columbus Attached Pressurized Module (APM). Inside the PM are single and double racks, and a workbench available for crew activities during the servicing periods when Station standard atmosphere is maintained. The RM supplies the basic power, communications and control for the configuration and houses ORUs containing the subsystems that supply the MTFF and its payloads with resources. Rollout solar arrays and a deployable antenna are attached. Attitude control is maintained through liquid propellant thrusters and cold-gas thruster systems for proximity operations. See Figure A-18.

CREW EMERGENCY RETURN VEHICLE (CERV)

Crew safety is an essential consideration in the development of Space Station. The return of the crew in the event of NSTS unavailability, a major system failure aboard the Space Station, injuries or illness may be required. Therefore, NASA has initiated a definition study for a Crew Emergency Return Vehicle (CERV).

The current concept is that the CERV would be capable of launch on the NSTS or ELV, berthing at the Space Station in a quiescent mode for extended periods, separation from the Space Station, limited orbital operations, guided entry from Earth orbit to a preselected landing site on Earth, and final landing. To have these capabilities the CERV would include the following subsystems: electrical power, environmental control life support, thermal control, communications and tracking, data management, guidance, navigation and control, attitude control, propulsion, man systems, displays and controls, and structure. Future decisions on CERV development will be made after the system definition studies which are scheduled to begin in January 1988.

INDUSTRIAL SPACE FACILITY (ISF)

NASA and Space Industries Partnership entered into a Space System Development Agreement on August 20, 1985, in support of the development by

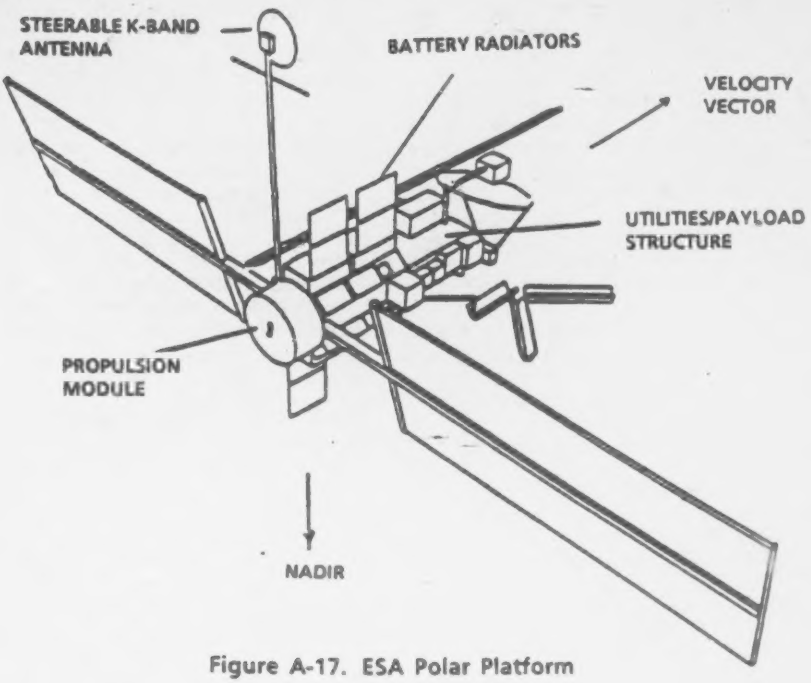

STEERABLE K-BAND
ANTENNA
BATTERY RADIATORS
VELOCITY
VECTOR
UTILITIES/PAYLOAD
STRUCTURE
PROPULSION
MODULE
NADIR

Figure A-17. ESA Polar Platform

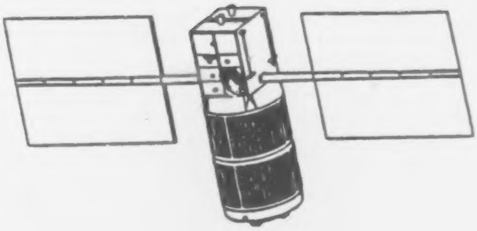


Figure A-18. ESA Man Tended Free Flyer

Space Industries of an Industrial Space Facility (ISF) – a man-tended, NSTS-deployed and NSTS-serviced free-flyer. Space Industries plans to deploy and operate the ISF several years prior to the Space Station initial operation.

The Space Station and ISF programs can be considered to be complementary and in some respects elements may be similar. There are aspects of the two programs that will be of mutual interest and of potential benefit to both NASA and Space Industries. The ISF will be developed commercially and independently of the Space Station Program.

The ISF is foreseen to operate for extended periods in orbit in an automated mode with brief interim periods docked to the Orbiter at which time it may be manned for servicing and research. During these manned periods, the crew may perform such functions as research, repairs, servicing, equipment change-out, harvesting of products, and cleaning and restocking or research and production apparatus.

The ISF Program will undertake a number of activities which are common to the Space Station Program. Therefore, cooperation and data exchange between the two programs could be mutually beneficial.

ASSEMBLY SEQUENCE

The following assembly sequence is the reference upon which NASA, U.S. industry, and the potential international partners will base their detailed Space Station design and development. This sequence may change, but at this time, it is the baseline sequence for the Space Station Program.

The assembly sequence consists of 20 NSTS launches including 13 for the manned base assembly, four for logistics, two for outfitting and user payloads, and one for the deployment of the U.S. polar platform. Additionally, two Ariane launches are planned for the deployment of the ESA polar platform and the ESA Man-Tended Free Flyer. See Table A-1.

The U.S. laboratory module will be launched on assembly flight MB-6. It will be partially outfitted, containing approximately 25 percent of the 44 equipment racks it will ultimately hold. The module will include basic support systems such as power, air conditioning, and water. A man-tended capability will be achieved with this flight. Flight OF-1 will be for outfitting the U.S. laboratory.

Permanently manned capability with a crew of four will be achieved with assembly flight MB-9. The flight will deliver logistics modules and equipment capable to sustain the crew.

Table A-1. *Reference Assembly Sequence*

FLIGHT		DESCRIPTION/MANIFEST	
1.	(MB-1)	18.75 PV POWER, TRUSS, FTS, ERECTOR SET, AVIONICS, RCS	
2.	(MB-2)	18.75 PV POWER, TRUSS, RCS, ATT. PAYLOADS	
3.	(MB-3)	AFT NODES, RCS	
4.	(MB-4)	TCS, MSC, PAYLOADS, RCS, SSEMU	
5.	(MB-5)	AIRLOCKS (2), SSRMS, PAYLOADS, POINTING SYSTEM	
6.	(P-1)	U.S. POLAR PLATFORM (WTR)	
7.	(MB-6)	U.S. LAB MODULE	MTC
8.	(OF-1)	LAB MODULE OUTFITTING	
9.	(MB-7)	U.S. HAB MODULE	
	(A-1)	ESA POLAR PLATFORM, ARIANE-5	
10.	(MB-8)	FORWARD NODES, CUPOLA, OUTFITTING	
11.	(MB-9)	CREW (4), LOGISTICS, OUTFITTING	PMC
12.	(MB-10)	18.75 PV POWER (2), TRUSS	
13.	(L-1)	LOGISTICS, OUTFITTING, P/L, CREW	
14.	(MB-11)	JEM, EF #1, CREW (8)	
15.	(L-2)	LOGISTICS, CREW	
16.	(MB-12)	ESA MODULE	
17.	(L-3)	LOGISTICS, OUTFITTING, CREW	
18.	(MB-13)	ELM, EF #2, P/L, OUTFITTING	
19.	(L-4)	LOGISTICS, OUTFITTING, P/L, CREW	
20.	(OF-2)	OUTFITTING, SPDM	
	(A-2)	ESA MTFF (ARIANE)	

KEY

A = Ariane
HAB = Habitation
L = Logistics
LAB = Laboratory
MB = Man Based
OF = Outfitting
P = Platform

APPENDIX B
REFERENCE DOCUMENTS

Document Number	Reference Documents
TBD	Program Requirements Document, August 15,1987.
JSC 30000	Program Definition and Requirements Document.
JSC 30456	Space Station System Engineering Process Requirements. December 30, 1986.
JSC 30255	Baseline Configuration Document. February 15, 1987.
JSC 30257	Architectural Control Document: Man Systems. January 15, 1987.
JSC 30262	Architectural Control Document: Environmental Control and Life Support System. Undated.
JSC 30263	Architectural Control Document: Electrical Power January 15, 1987.
JSC 30264	Architectural Control Document: Fluid Management Systems. January 15, 1987.
	Management Publications
NHB 1700.1	NASA Safety Manual
NHB 5300.4 (1A)	Reliability provisions for Aeronautical Space and System Contractors.
NHB 1700.7A	Safety Policy and Requirements for Payloads Using the STS.
KHB 1700.7A	STS Payload and Ground Safety Handbook.

APPENDIX C
ACRONYM LIST

A&R
Automation and Robotics
ACD
Architectural Control Document
APAE
Attached Payloac Accommodation Equipment
APM
Astronaut Positioning Mechanism
ATCS
Active Thermal Control System

C&T
Communication and Tracking
CAD
Computer Aided Design
CAE
Computer Aided Engineering
CCB
Configuration Control Board
CCZ
Command and Control Zone
CDR
Critical Design Review
CEI
Contract End Item
CERV
Crew Emergency Return Vehicle
CSD
Contract Start Date
CUP
Consolidated Utilization Plan
CY
Calendar Year

DCR
Design Certification Review
DDT&E
Design, Development, Testing and Evaluation
DMS
Data Management System

ECLS
Environmental Control Life Support
ECLSS
Environmental Control Life Support System
EEE
Electrical, Electronic and Electromechanical
ELM
Experiment Logistics Module

ELV
Expendable Launch Vehicle
EMU
Extravehicular Mobility Unit
EPS
Electrical Power System
ESA
European Space Agency
ESC
Engineering Support Center
EVA
Extravehicular Activity

FEL
First Element Launch
FMEA
Failure Modes and Effects Analysis
FMS
Fluid Management System
FRR
Flight Readiness Review
FSE
Flight Support Equipment
FTS
Flight Telerobotic Servicer
FY
Fiscal Year

GN&C
Guidance, Navigation, and Control
GPS
Global Positioning System
GSE
Ground Support Equipment
GSFC
Goddard Space Flight Center

JEM
Japanese Experiment Module
JPL
Jet Propulsion Laboratory
JSC
Johnson Space Center

KSC
Kennedy Space Center
kW
Kilowatt

LCVG
Liquid Cooling Ventilation Garment
LeRC
Lewis Research Center

MOU
Memorandum of Understanding
MPAC
Multipurpose Application Console
Mpbs
Megabits per second
MRDB
Mission Requirements Data Base
MRS
Mobile Remote Servicer
MSC
Mobile Servicing Centre
MSFC
Marshall Space Flight Center
MSIF
Multi-System Integration Facility
MSS
Mobile Servicing System
MTC
Man Tended Capability
MTFF
Man Tended Free Flyer

NASA
National Aeronautics and Space Administration
NRC
National Research Council
NSC
National Security Council
NSTS
National Space Transportation System

OAST
Office of Aeronautics and Space Technology
OCP
Office of Commercial Programs
OMB
Office of Management and Budget
OMS
Operations Management System
OMV
Orbital Maneuvering Vehicle
ORR
Operations Readiness Review
ORU
Orbital Replacement Unit
OSE
Orbital Support Equipment
OSF
Office of Space Flight

OSO
Office of Space Operations
OSSA
Office of Space Science and Applications
OSTP
Office of Science and Technology Policy

PAM
Payload Accommodations Manager
PCC
Program Coordination Committees
PDR
Preliminary Design Review
PLC
Pressurized Logistics Carrier
PMC
Permanently Manned Capability
PMS
Performance Measurement System
POIC
Payload Operations Integration Center
PORR
Preflight Operations Readiness Review
PRR
Program Requirements Review
PSC
Program Support Contractor
psi
pounds per square inch

RMS
Remote Manipulator System
RFP
Request for Proposal

SE&I
System Engineering and Integration
SPDM
Special Purpose Dextrous Manipulator
SRM&QA
Safety, Reliability, Maintainability, and Quality Assurance
SSCB
Space Station Control Board
SSCC
Space Station Control Center
SSE
Software Support Environment
SSIS
Space Station Information System
SSPF
Space Station Processing Facility
SSPO
Space Station Program Office

SSPSC
Space Station Platform Support Center
SSSC
Space Station Support Center
SSTF
Space Station Training Facility
SSUB
Space Station Users Board

TCS
Thermal Control System
TDRS
Tracking and Data Relay Satellite
TDRSS
Tracking and Data Relay Satellite System
TMIS
Technical and Management Information System
TOP
Tactical Operations Plan

ULC
Unpressurized Logistics Carrier
UOB
Utilization and Operations Board

WBS
Work Breakdown Structure

NASA
National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: XC:JJH:brb

JAN 15 1988

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JAN 15 1988
Committee on Science, Space
and Technology

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Pursuant to the National Aeronautics and Space Administration Authorization Act of 1988, P.L. 100-147, Section 113(b), we are forwarding the enclosed information on the geographic distribution of NASA awards during fiscal year 1987. As you will see by the data, NASA has a wide geographic spread of awards and does not use any geographic criteria in making selections, except in rare instances.

We will be happy to meet with you or your staff to discuss this data or to provide any additional information at your convenience.

Sincerely,

Jon A. McBride
Assistant Administrator
for Congressional Relations

Enclosure

cc: Honorable Manuel Lujan, Jr.

GEOGRAPHIC DISTRIBUTION OF NASA AWARDS

Under Sec. 113(b) of P. L. 100-147, NASA was asked to report on the extent to which consideration of geographic distribution of Federal research funds was given during fiscal year 1987. The following is provided:

During FY 1987, 50 states and the District of Columbia participated in NASA's direct awards of contracts and grants of $25,000 and over, as shown on the attached table. NASA does not track geographic distribution of procurements under $25,000. In addition, NASA's data system does not readily separate out procurements based on the type of funds (R&D, R&PM, etc.) used, so this report includes NASA procurements funded with both R&D and non-R&D appropriations in FY 1987. The attached table also excludes awards placed through other Government agencies and those performed outside the U.S. It should also be noted that these prime contract dollars were distributed even further through subcontracts.

The categorization by state is based on the location where the items are to be produced or supplied from stock; where the services will be performed; or with respect to construction contracts, the construction site.

NASA does not use any geographic criteria in making selections for awards, except in rare instances where it is a functional necessity of the procurement; e.g., on-call emergency services which may require that the contractor be within a certain distance or travel time of the facility being serviced. In compliance with the Competition in Contracting Act, NASA uses evaluation criteria to assess technical competence, cost reasonableness, experience and past performance, and certain other factors.

It is NASA's view that use of any artificial considerations merely to further diversify the geographic spread of funds would violate the Competition in Contracting Act. The Comptroller General has ruled that geographic criteria must be reasonably related to the requirement being procured. NASA's aim is to obtain the best available research at the most reasonable cost. Proposals must be evaluated on their merits and how well they meet the requirements, not on the basis of the offeror's location. Nevertheless, as the attached table shows, we have a wide geographic spread of awards. Therefore, specific efforts to obtain geographic distribution are not considered appropriate.

U.S. GEOGRAPHICAL DISTRIBUTION OF NASA PRIME CONTRACT AWARDS FISCAL YEAR 1987

STATE	TOTAL (THOUSANDS)	BUSINESS (THOUSANDS)	EDUCATIONAL & NONPROFIT (THOUSANDS)
TOTAL	$6,791,565	$6,366,171	$425,394
ALABAMA	463,551	451,672	11,879
ALASKA	3,333	46	3,287
ARIZONA	24,035	12,912	11,123
ARKANSAS	393	193	200
CALIFORNIA	2,224,687	2,140,282	84,405
COLORADO	113,036	99,350	13,686
CONNECTICUT	162,600	161,695	905
DELAWARE	2,334	1,882	452
DIST COLUMBIA	49,275	29,232	20,043
FLORIDA	682,070	677,527	4,543
GEORGIA	26,931	23,120	3,811
HAWAII	5,507	170	5,337
IDAHO	271	--	271
ILLINOIS	16,173	6,199	9,974
INDIANA	9,899	6,835	3,064
IOWA	6,914	50	6,864
KANSAS	7,995	6,353	1,642
KENTUCKY	780	57	723
LOUISIANA	303,456	302,253	1,203
MAINE	695	367	328
MARYLAND	620,268	587,041	33,227
MASSACHUSETTS	63,310	20,255	43,055
MICHIGAN	16,166	6,009	10,157
MINNESOTA	14,641	12,648	1,993
MISSISSIPPI	68,341	66,836	1,505
MISSOURI	8,640	5,924	2,716
MONTANA	215	--	215
NEBRASKA	853	103	750
NEVADA	505	251	254
NEW HAMPSHIRE	9,287	3,715	5,572
NEW JERSEY	126,995	123,436	3,559
NEW MEXICO	54,970	50,395	4,575
NEW YORK	68,182	49,366	18,816
NORTH CAROLINA	7,561	878	6,683
NORTH DAKOTA	106	45	61
OHIO	131,299	114,835	16,464
OKLAHOMA	3,118	--	3,118
OREGON	3,491	1,618	1,873
PENNSYLVANIA	110,416	103,666	6,750
RHODE ISLAND	2,585	766	1,819
SOUTH CAROLINA	1,049	574	475
SOUTH DAKOTA	444	87	357
TENNESSEE	15,946	13,040	2,906
TEXAS	764,386	725,711	38,675
UTAH	289,036	287,159	1,877
VERMONT	740	697	43
VIRGINIA	240,589	219,418	21,171
WASHINGTON	42,944	38,451	4,493
WEST VIRGINIA	819	584	235
WISCONSIN	20,216	12,468	7,748
WYOMING	512	--	512

NASA
National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: XC:AMP:brb

JAN 20 1988

RECEIVED
FEB 3 1988
Committee on Science, Space,
and Technology

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

The purpose of this letter is to apprise you of our current activities related to the recommendations in your committee report accompanying the FY 1988 NASA Authorization Bill (Report 100-204) concerning science on the Space Station. For your convenience, I have excerpted the language in the report, followed by comments on the status of each recommendation.

1. NASA should take positive steps toward acquiring an extended duration capability Orbiter as recommended by the Task Force on the Scientific Uses of the Space Station.

NASA has conducted an extensive study on this subject, and a "Report to the Congress on an Extended Duration Orbiter" was transmitted November 23, 1987. In summary, the study showed that a sixteen day shuttle mission would reduce payload capability by approximately 8100 lb. for ascent and 4900 lb. for descent, but may substantially benefit space science, technology, applications and commercial endeavors, both before and during the Space Station era. Although it does not appear that an EDO would be of substantial benefit to the assembly and operation of the Space Station, it would increase the ability of the users to prepare for the Space Station. At an estimated development cost of approximately $126 million, it is anticipated that one EDO would be available in 45 months from development start date. Given the current assumptions based on the analysis to date, NASA could implement an EDO capability, but it will have to compete against all other NASA programs for funding. Specifics of this study can be found in the report previously mentioned.

2. Announcements of opportunity should be issued for various classes of experiments within the pressurized volume and for attached payloads as soon as the availability and technical characteristics of these opportunities can be baselined.

Definition studies and advanced technology development have been initiated for many payloads. Specific payloads to be flown will be selected through a peer-reviewed Announcement of Opportunity process. It is anticipated that the early Space Station attached payload selections will begin during the last quarter of calendar year 1988, and payload selections for the pressurized modules will begin at approximately the same time for some of the life sciences experiments. The Office of Space Science and Applications (OSSA) Microgravity Science and Applications Division plans to release a NASA Research Announcement for materials science payloads near the end of FY 1988.

3. A prioritization of specific materials science and life science activities should be developed such that meaningful planning of resources aboard the manned element can be facilitated.

OSSA is currently in the process of preparing a plan, "OSSA Payloads for Phase I of the Space Station Complex", which should be available by the end of February 1988. It will outline in some detail what our intentions are for the use of the Space Station Complex, and will cover attached payloads, payloads for the pressurized volume, and payloads for the polar platforms. This plan for utilization of the baseline Station will take into consideration launch capabilities and Space Station resources. These constraints will result in the prioritization of materials science and life science areas of research, which will ultimately be reflected in the payload complements. However, we are not prioritizing specific experiments at this point in time. This plan is expected to be complete before the Space Station Preliminary Requirements Review, which is currently scheduled for March 1988.

4. An organizational focal point within the Office of Space Science and Applications should be established to integrate the needs of the various science disciplines and develop a unified science utilization plan.

In September 1987, Dr. Lennard A. Fisk, Associate Administrator for Space Science and Applications appointed Mr. A. V. Diaz as the OSSA Assistant Associate Administrator for Space Station. Dr. Fisk also announced a reorganization which included the designation of the Flight Systems Division as the organizational entity within OSSA which is responsible for the utilization planning for Space Station. Within the Flight Systems Division, the Space Station Utilization Branch is the focal point for integration of OSSA Space Station requirements, and interface with the Space Station Program Office.

5. NASA should commit to a Science Applications Information System and the interface with this system should be an explicit part of the design baseline.

Within OSSA, the Communications and Information Systems Division is responsible for the Science and Applications Information System (SAIS) development. A significant accomplishment during FY 1987 was the development of SAIS Requirements by the SAIS

Working Group as well as the generation of an SAIS Operations Concept Document. OSSA endorses the SAIS and has allocated FY 1987 and anticipated FY 1988 funds to SAIS architecture development activities. Basic SAIS concepts, such as Transaction Management, have been baselined in the Space Station program requirements documents. In general, the Space Station Information System accommodates the SAIS, and appropriate interfaces are being established.

> 6. NASA should establish science test beds to develop expert systems, teleoperation, and robotic capabilities. These should emphasize science disciplines most in need of automated technologies such as materials science.

Phase I of a Telescience Testbed Program is underway, and is under contract as the Telescience Testbed Pilot Program (TTPP). The principal TTPP objectives are to:

1. Involve users in the development of Space Station Era Information Systems;
2. Test the applicability and feasibility of emerging technologies and methodologies to the implementation of Telescience;
3. Validate system requirements and investigate implementation options.
4. Gain experience in the use of computer networking to provide remote interactive access to system services for increasing scientific productivity and facilitating interdisciplinary research; and
5. Demonstrate the ability of universities to address NASA problems, work with NASA system designers, and collaborate in the resolution of issues.

Fifteen universities are participating in the first phase of this program. In FY 1988, NASA Field Centers will be significantly involved in this activity, and the second phase of the program, which includes a broader research announcement to the science community, is scheduled to commence. OSSA budget plans for FY 1988 include funding for testbeds involving teleoperations, expert systems, and automation and robotics. Specific emphasis will be placed on the microgravity sciences, particularly by the NASA Field Center testbeds.

I hope that you find our activities to date as being responsive to your recommendations. Your continued interest in and support of NASA's Science and Applications programs are greatly appreciated and I look forward to our continued furtherance of Space Science and Applications activities on the Space Station.

Sincerely,

Jon A. McBride
Assistant Administrator
for Congressional Relations

cc: Honorable Manuel Lujan, Jr.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: XC:AMP:brb

JAN 21 1988

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Pursuant to Report 100-204 accompanying the NASA Authorization Act of 1988, I am hereby transmitting the agency's response to the Committee's direction that NASA's Technology Utilization Program report on projects underway in applied technology for employment, housing and education for the disabled, and the manner in which NASA disseminates information on such technology transfers. As you will see in the enclosed report, NASA's Technology Utilization Program is working actively to identify and apply technologies for meeting the needs of the disabled.

I hope you will find this information to be useful. We would be pleased to meet with the Committee staff to discuss further any aspect of this report or to provide any additional information you may require.

Sincerely,

Jon A. McBride
Assistant Administrator
for Congressional Relations

Enclosure

cc: Honorable Manuel Lujan Jr.

NASA TECHNOLOGY APPLICATIONS

MEETING THE NEEDS OF PEOPLE WITH DISABILITIES

The NASA Technology Utilization (TU) Division assists private companies, associations, and government agencies to make effective use of NASA's technological resources to improve U.S. economic competitiveness and to provide societal benefit. As part of this program, NASA works actively with private and public sector organizations to transfer NASA-developed technology into new, commercially available products for people with disabilities. NASA responds to the priority needs in rehabilitation as expressed by rehabilitation mission agencies, disability consumer groups, and industry to develop products that offer people with disabilities increased access to employment, education, housing, and recreational opportunities. Some of the agencies and consumer organizations that NASA has worked with in the past are listed in Figure 1. The NASA model for technology transfer in rehabilitation was commended in the U.S. Congress Office of Technology Assessment's 1982 report "Technology and Handicapped People."

Some of the current and more recent technology transfer projects to benefit people with disabilities are described briefly below, along with participating organizations.

Digital Hearing Aid

Hearing impairment is a wide-spread problem having adverse impact on the individual and on society in general. Sixty percent of older persons, or approximately 15 million people, are considered hard of hearing. Additional millions of younger people are hearing impaired due to illness, birth defects, or damage. People with hearing impairments tend to lose contact with their environment and with their friends and relatives, and societal barriers can limit education, employment, and recreational opportunities.

Currently available hearing aids use traditional analog technology in testing devices and in the hearing aid itself. Conventional aids rely on amplification of sound in the frequencies that are lost. This is a relatively simple approach that often leads to less than satisfactory performance. The Central Institute for the Deaf, in affiliation with Washington University, has brought together a joint development project with NASA Kennedy Space Center, the Veteran's Administration, and 3M Company to make digital hearing aid technology available to the hearing impaired population. This will be accomplished by transferring an experimental digital hearing device developed by the Central Institute for the Deaf into a commercially available product. Once digital hearing aids become widely available, people with severe hearing impairments will have a greater choice in the jobs and recreational activities accessible to them.

MISSION AGENCIES

Administration on Aging (AoA)
National Cancer Institute (NCI)
National Eye Institute (NEI)
National Hansen's Disease Center
National Heart, Lung, and Blood Institute
National Institute of Neurological and Communicative Disorders and Stroke (NINCDS)
National Institute on Aging (NIA)
National Institute on Disability and Rehabilitation Research (NIDRR)
National Institute of Arthritis, Diabetes, Digestive and Kidney Disorders
The Lighthouse
Veteran's Administration (VA)

CONSUMER ORGANIZATIONS

American Association of Retired Persons (AARP)
American Cancer Society (ACS)
American Society on Aging (ASA)
Association for the Advancement of Rehabilitation Technology
Association of Retarded Citizens (ARC)
Footwear Industries of America
Gerontological Society of America (GSA)
National Association of Area Agencies on Aging
National Easter Seal Society (NESS)
Paralyzed Veterans of America (PVA)
Prescription Footwear Association
President's Committee on Employment of the Handicapped
United Cerebral Palsy Association (UCPA)

Figure 1. Mission Agencies and Disability Consumer Groups Interacting with the NASA Technology Utilization Division.

Digital hearing aids offer the following improvements over traditional analog devices: an increased capability to adjust the sound amplification to the individual wearer's hearing loss, hence improved performance and user satisfaction; a reduction in feedback noise; and better performance in noisy environments. NASA's contribution of very large scale integrated (VLSI) circuit technology offered the packaging and performance breakthroughs that were needed to drive the project forward and to secure the participation of 3M Company. Commercial availability is expected in the beginning of 1991. The participants are 3M Company, Washington University at St. Louis-Central Institute for the Deaf, Veterans Administration, NASA Kennedy Space Center, and NASA Goddard Space Flight Center.

Bladder Fullness Monitor

The Association for Retarded Citizens (ARC) represents people with mental disability and their families nationwide. The ARC Bioengineering Program identified toilet training of children and adults with severe mental retardation as a major difficulty in current programs. These individuals either do not have or are unable to interpret an internal stimulus of the need to urinate, and standardized toilet training programs are unable to relate the toileting schedule to any internal stimulus or urge to urinate.

The Association for Retarded Citizens conceptualized a device that would provide feedback of bladder fullness to the individual as well as to the caregiver. NASA engineers, working with ARC, have developed a prototype device which uses ultrasound to monitor the tension in the back of the bladder wall, which has been proven to correlate to bladder volume. The monitor currently fits within a portable camera case and is undergoing field tests by the Association for Retarded Citizens. Custom integrated circuit design as well as further design optimization are expected to reduce the unit to a "walkman" size. Promising results to date suggest continued development, and a major health care and consumer products company is interested in eventual commercialization. Use of the bladder fullness monitor will hopefully reduce the incidence of incontinence and the stigma attached to it, and allow more people with mental disability to participate freely in education, employment, and social activities. Project participants include the Association for Retarded Citizens, National Institute on Disability and Rehabilitation Research, Medical College of Virginia, and NASA Langley Research Center.

UNISTIK Vehicle Controller

Access to transportation can be a major barrier for people with disabilities. While some types of public transportation may be accessible, it is independent personal transportation which ultimately provides opportunities in employment, education, and recreation and the hope for leading productive lives. NASA has worked with the Veteran's Administration and Johnson Engineering Corporation to develop a control system that will enable people with severe physical disabilities to drive a conventional motor vehicle. This is an especially significant development for persons with quadriplegia who have no appreciable motor function below the neck and shoulders.

The UNISTIK vehicle controller is based on technology originally used in the Apollo Lunar Rover where only one hand was used to accelerate, brake, and steer the vehicle. The UNISTIK uses a two-axis joystick to control electric motors; moving the stick forward depresses the accelerator pedal, rearward depresses the brake pedal, and left or right movements turn the steering wheel accordingly. The system uses "fly-by-wire" technology found in high speed aircraft rather than the conventional direct coupling of control to actuator. The UNISTIK is currently operational in a Ford Van and has been successfully driven by several persons with quadriplegia. Further refinement is expected to lead to a commercially available product which will open new doors to independent living for people with severe physical disabilities. The project participants are Johnson Engineering Corporation, Veterans Administration, and NASA Johnson Space Center.

Wandering Notification Device

Wandering behavior is exhibited by the mild to moderately cognitively impaired elderly, including those persons with Alzheimer's Disease and other dementias. Wandering has both direct and indirect effects on persons who wander and on their caregivers. On the one hand, the freedom to wander safely may help maintain the memory-impaired person's physical, psychological, and activities of daily living capabilities. On the other hand, wandering can expose the person to physical danger and even death. Indirect impacts of wandering include restriction of the person's freedom of movement and, in some cases, institutionalization. Both family and professional caregivers are affected by their fear for the person's safety and their feeling of responsibility to provide for that safety. The need for virtually constant surveillance is particularly devastating in the home where one or only a few caregivers have the responsibility for providing this surveillance.

Current products provide less than adequate solutions to this problem. NASA has entered into an Interagency Agreement with four other federal agencies to help design, develop, and produce a notification and locator device based on NASA and other technology which meets the needs of the target population. A Phase 0 Needs Assessment and Feasibility Study funded by the five sponsoring agencies was completed by NASA's Technology Applications Team. Through a competitive procurement, NASA has selected Cortrex Electronics, Inc., who markets a related product called Kare Alert as a collaborating manufacturer on this project. Cortrex, together with engineers at NASA Johnson Space Center, has begun work on Phase I, Engineering Design, with Phases II and III, Prototype

Development and Clinical Evaluation, to follow. The project is expected to take approximately two years to complete. Participants include Cortrex Electronics, Inc., Administration on Aging, National Institute on Aging, National Institute on Disability and Rehabilitation Research, Veterans Administration, Research Triangle Institute, Duke University, and NASA Johnson Space Center.

Hydraulic Body-Powered Upper Limb Prosthesis

Current figures show that there are approximately 100,000 upper limb amputees in the United States and that 50 percent of these wear some type of prosthesis. Of the 50,000 persons who wear prostheses, approximately 90 percent use body-powered devices while only 10 percent use the newer, externally powered, or "bionic", devices. Clearly, body-power is still the preferred means of control among upper limb amputees. However, the technology used in upper limb prostheses has not changed significantly since being developed in the 1950s. Aircraft technology spinoffs to shoulder harnesses and steel or plastic cables are still used for operation. Problems with cable prostheses include no active control of wrist function, harness discomfort particularly in the underarm area, and the outside mounting of cable hardware which leads to unattractive designs and excessive wear and tear on clothing.

Mr. Maurice LeBlanc, Director of the Rehabilitation Engineering Center at the Children's Hospital at Stanford, is being assisted by engineers at NASA Johnson Space Center to design and develop a body-powered prosthesis which would use a fluid control system to actuate the terminal device rather than the cable controls of current artificial limbs. The advantages of hydraulic versus cable control include less input force required by the user, improved appearance, and a more comfortable fit. Clearly, an improved body-powered upper limb prosthesis will help attract more nonwearers into becoming wearers and possibly increase the job and recreational opportunities available to them. Mr. LeBlanc has demonstrated his design in a proof-of-concept system, and is now working with the engineers at Johnson Space Center to develop the pump unit which will act as a force multiplier for transmitting the shoulder movements of the user to the gripping forces of the hand or hook. A working prototype has already been constructed and with modifications will be ready for preliminary clinical evaluation. Project participants are the Children's Hospital at Stanford Rehabilitation Engineering Center, National Institute on Disability and Rehabilitation Research, and NASA Johnson Space Center.

CAD/CAM for Custom Orthopedic Footwear

The requirement for orthopedic shoes can result from congenital foot disorders, such as trauma and biomechanical conditions, or may be secondary to systemic diseases such as arthritis and diabetes mellitus. Properly fitted footwear is critical to the prevention, alleviation and correction of foot disorders, regardless of etiology, and essential for productive, independent day-to-day living for these persons. Approximately 9.5 million pairs of orthopedic shoes are manufactured annually in the U.S., and the costs range from $400 to $750. The most influential factors causing the high cost and lengthy delivery time for custom orthopedic footwear are the complex manufacturing process and the decreasing number of skilled artisans capable of fabricating custom shoes.

In an effort to capture the expertise of these skilled craftsmen and to modernize an inadequate delivery system, the National Institute on Disability and Rehabilitation Research and NASA are currently supporting the development of a computer aided design/computer aided manufacturing (CAD/CAM) system for custom orthopedic footwear. NASA-developed technologies which are being evaluated for this project include composite materials, tactile sensing array transducers, and NASA computer software for CAD/CAM, artificial intelligence, and database management. The development of a written manual describing the prescription and custom last production processes has been completed as a first phase of the project. Project participants are Davis Shoe Company, National Institute on Disability and Rehabilitation Research, Veterans Administration, Research Triangle Institute, North Carolina State University, NASA Ames Research Center, and NASA Langley Research Center.

Cooling Garments for People with Thermoregulatory Disabilities

Cooling garments have the potential to benefit people with quadriplegia who, because of their inability to perspire below the level of injury, are often limited in their vocational and recreational activities in warm surroundings. Other potential users of these cooling garments include children and adults who undergo radiation treatments for cancer. Chemotherapy and other treatments often induce refractory fevers which are untreatable by conventional medications. Also, cooling applied to the scalp may help reduce the hair loss common to cancer therapy. In addition, aging and some diseases disrupt normal body thermoregulation, leaving these persons susceptible to hyperthermia and heat stroke in even moderate temperatures.

A project is underway to transfer liquid-cooled garment technology originally developed for use in astronaut's space suits to applications in rehabilitation and medical treatment. New developments in materials, pumps, and battery power have reduced the heavy, bulky suits once worn by astronauts to lightweight, portable, and inexpensive cooling vests. NASA has developed a prototype cooling vest for people with quadriplegia, and some commercial units are now available that with appropriate modifications could have a significant impact on the lives of these individuals. A study to specify the functional requirements of cooling garments for people with disabilities is being conducted by the NASA Applications Team. A low cost, commercially available cooling garment will reduce the barriers in jobs, travel, and recreation faced by people with thermoregulatory dysfunctions. The participants in this project are ILC Dover, Inc., National Institute on Disability and Rehabilitation Research, Research Triangle Institute, NASA Ames Research Center, and NASA Headquarters.

Low Vision Aids for Rehabilitation

There are over two million persons in the U.S. with low vision, a number which is increasing dramatically as the nation's population ages. Rehabilitation low vision aids consist of optical devices which provide magnification at the expense of field of view, or approaches which seek to improve illumination without increasing glare. The capabilities and usefulness of these current aids are limited by basic optical physics. However, recent advances in electro-optical technologies offer the possibility of substantially improved performance by providing non-uniform magnification, image/contrast enhancement, spatial remapping (to place images on healthy portions of the retina), contrast reversal, and other techniques not possible solely with conventional optics.

NASA has participated in two workshops related to improved technology for low vision rehabilitation, one with Wilmer Eye Institute of Johns Hopkins University and the other sponsored by an Interagency Workgroup on Technology and Aging. Four NASA Technology Utilization projects have been funded to investigate applications of specific NASA-developed electro-optic technologies. These include 1) use of comprehensive image processing software, developed for Earth remote sensing, for improved evaluation of patient visual performance; 2) use of a real-time spatial image remapper, developed for robotic vision, to remap images to healthy retina tissues; 3) use of real-time PIFEX image processing hardware in an improved closed circuit television (CCTV) system; and 4) adaptation of a head-mounted three dimensional visual display, developed for telerobotics, to low vision reading assessment and training. These projects are being managed as an overall program in technology transfer, and will be reviewed following the feasibility or early prototype stages. Participants include NASA-Ames Research Center, Jet Propulsion Laboratory, Johnson Space Center, National Space Technology Laboratories; Pennsylvania College of Optometry, University of Southern California, University of Houston, and Johns Hopkins University.

Ultrasonic Burn Depth Monitor

Burn injury severity is classified by depth of injury: superficial, partial thickness and full thickness burns. Partial thickness burns will heal satisfactorily, but full thickness burns require skin grafting. Thus the clinical course of treatment depends upon accurate determination of the depth of injury, which is currently based upon trained clinical judgement. No devices currently exist to aid in this judgement, and in questionable cases several days may pass while the progress of healing is monitored to determine if surgery is necessary. During this time, the patient is highly susceptible to infection, and, in fact, secondary infections are a major cause of mortality and morbidity in burn patients.

NASA physicists at Langley Research Center proposed that ultrasound could be used to detect the interface between destroyed and viable tissue in the burn wound. To detect this interface, instrument resolution would need to be better than 0.1 mm, which exceeded any current medical ultrasound equipment. NASA, working with a collaborative manufacturer, developed such an instrument. Initial animal studies conducted at the Medical College of Virginia demonstrated a 93% correlation with histological results. A preliminary clinical evaluation was conducted on three patients with successful results. Further development is required to improve the measurement techniques and signal processing electronics, and a larger series of clinical tests are planned. The project participants are Advanced Technology Laboratories, Medical College of Virginia, and NASA Langley Research Center.

Advanced Wheelchair Design

For people with limited mobility, wheelchairs offer independence in the home, school, and vocational environments. Critical to this independence is a wheelchair whose performance characteristics match the accessibility of the surroundings in which it will be used. In the past, wheelchairs made of steel and other metals have been heavy and often difficult to maneuver for people with disabilities, especially in confined spaces. Storage and transport also present barriers that must be overcome for wheelchair users. In addition, metal wheelchairs are subject to corrosion and fatigue which can result in costly repairs and shortened lifespans.

A collaboration between NASA's engineers and researchers in rehabilitation engineering has led to improved design techniques and better materials usage for wheelchairs. NASA expertise in composite materials fabrication and in engineering design analysis has been used to develop and fabricate a wheelchair made of advanced carbon composite materials. Composites offer a very high strength to weight ratio. This wheelchair weighs less than 25 pounds and can be folded and stored with little effort. A parallel effort has helped develop a composite chair that is now being used by the airline industry to provide lavatory access to people with limited mobility. Currently, work is underway to assess the market needs for other improved wheelchair designs so as to improve the access to education, employment and recreational environments for people with disabilities. The participants in this project are University Technology Corporation, National Institute on

Disability and Rehabilitation Research, University of Virginia Rehabilitation Engineering Center, Research Triangle Institute, and NASA Langley Research Center.

Speech Autocuer

There are over one million people in the U.S. who cannot hear more than words shouted in an ear. The successful development of a wearable, real-time speech perception aid has the potential to improve the economic status and quality of life for these individuals. Research has shown that people who are hard of hearing can perceive speech accurately through a prosthesis based on Cued Speech. Used in a device called the Autocuer, cued speech presents automatically derived visual cues in real-time to a wearable eyeglass display, which when used in combination with lip reading, enables accurate speech perception by people who are hearing impaired.

NASA's contribution to this development project has been the complementary metal-oxide semiconductor (CMOS) electronics technology that is being used in the wearable microcomputer for analyzing connected speech. Prototype evaluations with hard of hearing subjects have been successful and the Autocuer is now being enhanced for commercial production. The participants in this project are Power, Inc., Research Triangle Institute, Gallaudet University, Veterans Administration, and NASA Goddard Space Flight Center.

Functional Electrical Stimulation

Paralysis secondary to paraplegia or quadriplegia creates tremendous physical barriers for people who are often well qualified and highly motivated to participate in education, employment, and recreational activities. The use of wheelchairs has helped integrate people with spinal cord injuries into many activities, however, the possibility that inactive muscles and limbs will once again become functional offers unimaginable hope to these people. In addition, the physical and mental benefits of being upright and walking have been proven by the medical community.

Functional electrical stimulation, or FES, using a computer-controlled, multi-channel, externally mounted stimulator has enabled lower-limb paraplegics to stand, walk a few steps, and even negotiate stairs. At present, the electronics and associated hardware are cumbersome and inappropriate for everyday use. The ultimate goal to be realized will use a simplified control system that can be implanted in the individual. NASA is contributing packaging techniques and electronics reliability technology to help develop a workable implantable design for a stimulation system. While the immediate effort will help researchers investigate the feasibility of implantable FES devices, the long-term objective is to enable people who are paralyzed to stand reliably and have a limited walking capability. The project participants are the Veterans Administration, Case-Western Reserve University, Rancho Los Amigos Rehabilitation Hospital, National Institute on Disability and Rehabilitation Research, NASA Goddard Space Flight Center, and NASA Jet Propulsion Laboratory.

NASA disseminates information about its technology transfer program and on specific projects for people with disabilities through national organizations, publications, and conferences; journal articles; professional newsletters; and workshops. The following are just some of the mechanisms used in the past year to inform people about NASA Technology Utilization activities related to disability.

Publications

- Bioengineering and Rehabilitation (NASA publication, 1985)
- The Wall Street Journal
- The New York Times
- Omni Magazine
- SOMA- Engineering for the Human Body (journal)
- The Aging Network News (newsletter)
- Health News
- Cable News Network
- IEEE Spectrum (journal)
- Generations (journal)
- Great Atlas of Space (foreign publication)
- Rehabilitation Technology Review (newsletter)
- American Society on Aging

Presentations

- RESNA- Association for the Advancement of Rehabilitation Technology
- National Conference on Technology and Aging
- FOCUS 86
- Gerontological Society of America
- Prescription Footwear Association
- Footwear Industries of America
- IEEE Engineering in Medicine and Biology Conference
- President's Committee on Employment of the Handicapped

Workshops

- Low Vision Workshop

The NASA Technology Utilization Program has earned a reputation as a national leader in the development of applied technology to benefit people with disabilities, and expects to continue these activities with the highest level of commitment in the years to come.

NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546
Office of the Administrator

January 29, 1988

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed is a preliminary report on cost effective space transportation for the Space Station requested of NASA by the National Aeronautics and Space Administration Authorization Act of 1988 (P.L. 100-147). The report, "Space Transportation for the Space Station," provides an examination of NASA's space transportation capabilities, the Space Station transportation requirements and alternatives, and the cost implications of each alternative. Approaches for space transportation studied include the Space Shuttle, existing and planned expendable launch vehicles, and heavy-lift launch vehicles.

The report supports the conclusions of recent studies that the Space Shuttle is uniquely suited for the majority of the current assembly and operational requirements of the Space Station Program. Alternative expendable and heavy-lift launch systems are not required for Space Station assembly; however, the use of current or planned unmanned launch vehicles could lead to reduced reliance on the Shuttle. Further, the report concludes that a routine operational rate of five Shuttle flights per year will support crew rotation requirements, provide operational flexibility, and satisfy Space Station logistics requirements.

This report was completed prior to the final action by the Appropriations Conference Committee on the NASA FY 1988 request. The Conference Committee report directed NASA to "...provide the committees a detailed plan...rescoping and rescheduling the Space Station activities consistent with 1988 and 1989 revised budgets." Such changes as may be necessary to comply with this direction are being studied and, therefore, are not reflected in the enclosed report. However, it is not expected that any resulting program changes will alter the conclusion of the report.

We would welcome an opportunity to review the report and the subject of Space Station transportation with you and your colleagues.

Sincerely,

James C. Fletcher
Administrator

Enclosure

cc: Honorable Manuel Lujan, Jr.

National Aeronautics and
Space Administration

SPACE TRANSPORTATION FOR THE SPACE STATION

A NASA Report To Congress

NASA OFFICE OF SPACE FLIGHT

WASHINGTON, D.C.

January 1988

Attachment 2

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SPACE TRANSPORTATION FOR THE SPACE STATION
A NASA REPORT TO CONGRESS

Preface

This report is submitted by the National Aeronautics and Space Administration (NASA) in response to a directive from Congress ". . . to submit a preliminary report on the cost-effective use of space transportation systems for the launch of space station elements during the development and operation of the space station." Section 109 of the National Aeronautics and Space Administration Authorization Act of 1988 (PL 100-147) specifies " . . . the sense of the Congress that the launching and servicing of the space station should be accomplished by the most cost-effective use of space transportation systems, including the space shuttle and expendable launch vehicles."

This report reflects the NASA Administrator's response to specific components of the Act as follows:

- the requirement for Space Shuttle launches;
- the use of existing expendable launch vehicles;
- the potential use of heavy lift launch vehicles; and
- the risk of capital losses.

The report was prepared jointly by the NASA Offices of Space Flight and Space Station with the assistance of the Office of Space Science and Applications.

Summary

A September, 1987 "NASA Space Station Transportation Study" confirmed that the Space Shuttle, with its proven capabilities of manned flight, extravehicular activity base, rendezvous and station keeping, remote payload manipulation and on-orbit endurance is uniquely suited for the majority of the current assembly and logistics requirements of the Space Station program. The study concluded that existing expendable launch vehicles could be modified and augmented to accomplish limited cargo delivery tasks. Also, a heavy lift launch system, once developed, could be used for large scale delivery operations. While alternative expendable and heavy lift launch systems are not required for Space Station assembly or operations, use of unmanned launch vehicles could lead to a reduced reliance on Space Shuttle support. The Space Station program is conducting a detailed study of the capability to accommodate unmanned launch vehicles including a definition of appropriate interface and safety requirements.

During the Space Station manned base assembly phase, there is an explicit need for manned extravehicular activity to erect the Space Station elements. With its present capabilities, the Shuttle can deliver and support assembly of all Station elements. An increase in performance from advanced solid rocket motors would reduce the number of Shuttle flights required to assemble the Station. An unmanned launch vehicle could deliver selected elements, but it would need to be in the heavy lift category to carry all of the required masses. Shuttle flights could be reduced during the assembly phase and Station elements could be delivered completely outfitted, but a new heavy lift launch system would be required. The questions of automatic or remote docking, use of an Orbital Maneuvering Vehicle and Shuttle-based extravehicular activity requirements would need to be addressed if the use of an unmanned launch system to augment Space Shuttle launches were to be considered.

During the operations phase, space transportation support for the Space Station is driven by Station crew rotation requirements, associated Shuttle crew capacities and limitations, and payload requirements. As the Shuttle is the only means available for routine Station crew delivery and return, the rate of required crew rotation dictates the minimum Shuttle flight rate required to support sustained Station operations. Early analyses concluded that the planned Space Station crew staytime on orbit required a baseline Shuttle flight rate of eight flights per year in support of Space Station. As a result of a review of crew staytime implications and limitations, a new plan was developed that extends the planned crew staytimes to 180 days. This plan includes the development of biomedical technologies to insure crew health and productivity during long duration missions.

With the longer crew staytimes, NASA has concluded that the Shuttle, with the current ascent and return capabilities, will support the resulting crew rotation requirements at a reduced rate of five flights per year, provide operational flexibility, and satisfy Space Station operational resupply and return requirements. The reduction of Shuttle flights dedicated to support Space Station operations significantly increases schedule flexibility for the Shuttle as well as providing manifest opportunities for other scientific and planetary payloads.

Introduction

In preparing this report on cost-effective transportation for the Space Station program, all modes of United States space transportation were examined including the Space Shuttle, existing and planned expendable launch vehicles, and proposed heavy lift launch vehicles. Alternative manifesting and manned base assembly scenarios were examined and various operations support schemes were reviewed. The result is a technical solution that matches existing transportation capabilities to Space Station needs. The solution also accommodates the use of potential future transportation systems or the incorporation of improvements to the Shuttle as they are realized. Space Station assembly and operations plans were carefully devised to take advantage of such new transportation developments without major changes in the program.

This report draws heavily on the "NASA Space Station Transportation Study" which was completed in September 1987. That study was the result of five months of intensive effort which began in April 1987. The study considered the use of existing expendable launch vehicles and derived its flight requirements from the Space Station revised baseline program of April 1987. The study focused on the manned base assembly, with the assumption that the U.S. polar platform would be launched on an expendable launch vehicle. An early sensitivity analysis was completed in May 1987, which resulted in a target rebaselining of the Space Station program from eight to five Space Shuttle flights per year. Results of the sensitivity analysis were briefed to the NRC Committee on Space Station on July 10, 1987 and on August 3, the NRC Committee was briefed on the preliminary results of the more comprehensive Transportation Study which it used in its final report of September 14, 1987. Recommendations of that NRC report have been incorporated in the Space Station assembly plans.

As the Transportation Study was being prepared, the Space Station Program made major changes in its assembly and operations plans; the National Space Transportation System made significant performance improvement plans; and the NASA Life Sciences Division developed an extended on-orbit crew staytime plan which is key to optimizing Space Station operations transportation. These changes were expedited by close coordination among the NASA Program Offices during the Transportation Study and in the course of its review and approval by the NASA Administrator. This close coordination is continuing and can be expected to produce further improvements as Space Station development matures. As a result of the Transportation Study, there is sufficient understanding of the space transportation systems options, life sciences expectations and the Space Station Program to define the most effective mode of Space Station transportation at this time.

I. Space Station Transportation Requirements

Space Station transportation requirements may be divided into two categories, the requirements for launch and assembly and the requirements for continuing operations. The Space Station has been designed to be assembled over a period of about three years in the mid-1990's. Prior to the recent Congressional action on the FY 1988 budget for the Space Station, the target dates were: first element launch in 1994, man-tended capability in 1995, and permanently manned capability in 1996. Completion of assembly, including the international elements, was planned for 1997. Schedule dates are under review. The analyses reflected in this study are not expected to be materially changed by changes in assembly schedules.

Space Station Assembly

Delivery of the baseline Space Station manned base configuration (Figure 1) will require launching a total of 450,000 pounds of mass to a 220 nmi circular orbit at an inclination of 28.5 degrees. To accomplish this, the Space Station must be divided into launch packages consistent with the ascent performance capability and the payload size constraints of the launch system. These packages must contain the components necessary to be self-sustaining in orbit until integrated with other package(s) and they must possess the characteristics necessary to facilitate the integration operation. As a result of these design drivers, it has been necessary to standardize the launch packages to an available transportation system affording

SPACE STATION CONFIGURATION

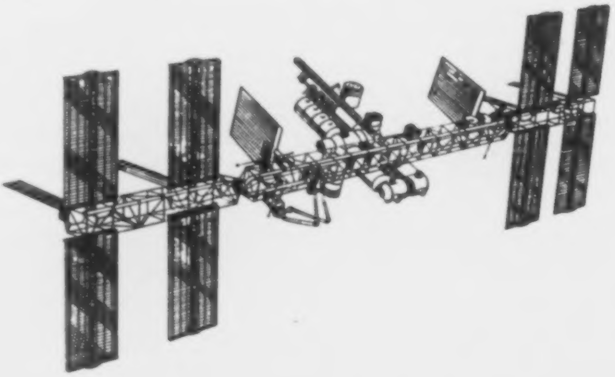


FIGURE 1

the ability to perform the integration operations and providing the largest possible payload mass and volume delivered to orbit. The large mass is needed to reduce the number of launch packages and the large volume will permit the greatest flexibility in laboratory and component design.

The Space Shuttle is an existing launch system with the largest payload mass and volume capability available for both launch and return. It possesses two means of facilitating the Station assembly component integration operations; these are Shuttle based extravehicular activity (EVA) and the remote manipulator system. It was decided at the outset of the program, therefore, to size the Space Station launch packages to take advantage of the Shuttle payload accommodations capabilities. This decision does not preclude the use of other launch systems. For Space Station assembly operations, any combination of an alternative launch system and the Shuttle will require dual compatibility for a launch in the design configuration on either the Shuttle or the alternative system. The elements of this combination will be defined in a cost effective manner.

As presently planned, to complete the Space Station will require 19 Shuttle flights (Figure 2). The launch packages will be designed for assembly by two Shuttle EVA crewmen with the assistance of the Shuttle remote manipulator system, a mechanical truss erector, a flight telerobotics servicer, and the Station based Canadian mobile servicing system. Assembly of each package will be designed to be accomplished in two six-hour EVA periods during a single Shuttle visit.

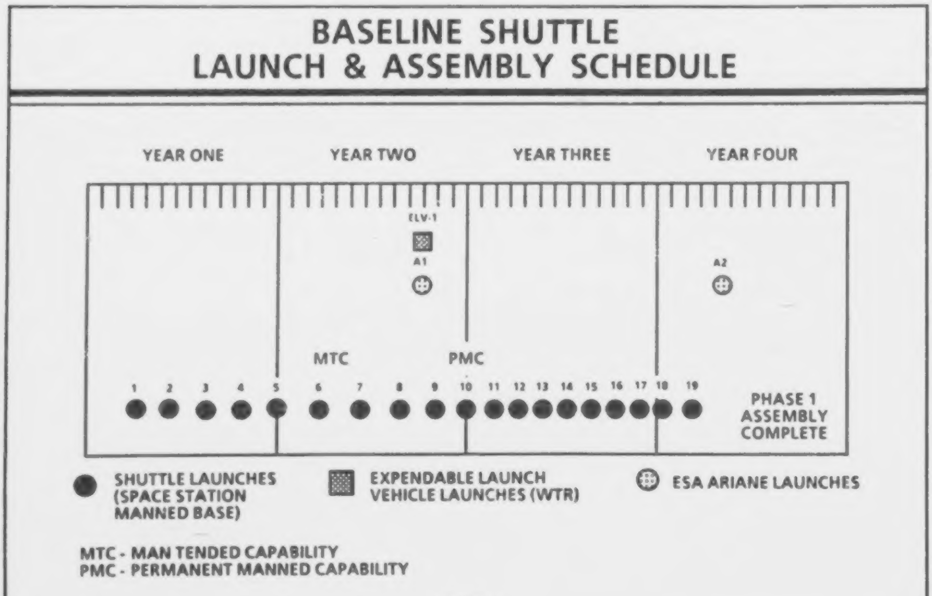


FIGURE 2

Space Station crew transportation will be required beginning with the launch of the laboratory module to provide an interim man-tended capability to support selected payloads and experiments during Shuttle visits prior to permanently manned capability when a Station crew will be continuously present. Permanently manned capability will be achieved with the launch of the habitation module. At that point the Station will be capable of supporting a crew of up to eight people. Space Station housekeeping logistics requirements during the assembly phase will gradually increase to the operational level.

Space Station Operations

At the conclusion of the assembly phase, the transportation system must provide a regular schedule for resupply and return of materials and for rotation of the Space Station crew. As shown in Figure 3, annual requirements for the operational phase of the program are 180,000 pounds up-mass and 156,000 pounds down-mass. Additional up-mass requirements, to be defined by the international partners, are expected to be in the range of 10,000 to 15,000 pounds. Some of the down-mass, about 16,000 lbs. per year, is expected to consist of disposable items (trash) that may be dealt with by other means.

SPACE STATION OPERATIONS
RESUPPLY AND RETURN REQUIREMENTS

CARRIERS	62,754
• Pressurized	50,208
• Unpressurized	7,700
• Fluids & Gases	4,846

USERS	72,800
• Rack Changeout	8,400
• Attached Payload Changeout	7,000
• Large Payload Additions	15,000
• Payload Resupply Logistics	42,400

STATION & CREW	44,504
• Crew Support	15,400
• EVA Support	1,863
• Fluids & Gases	1,588
• FTS	600
• MSC	2,602
• Miscellaneous	356
• System Spares	22,095

RESUPPLY REQUIREMENTS

ANNUAL 180,058

CARRIERS	62,754
• Pressurized	50,208
• Unpressurized	7,700
• Fluids & Gases	4,846

USERS	55,060
• Rack Changeout	8,400
• Attached Payload Changeout	7,000
• Large Payloads	1,500
• Payload Resupply Logistics	38,160

STATION & CREW	38,063
• Crew Support	10,547
• EVA Support	1,863
• Fluids & Gases	0
• FTS	600
• MSC	2,602
• Miscellaneous	356
• System Spares	22,095

RETURN REQUIREMENTS

ANNUAL 155,877

FTS - Flight Telerobotic Servicer
MSC - Mobile Servicing Center
Note - Excludes TBD international partners system spares requirements

FIGURE 3

Crew rotation planning requires two teams of four persons to serve overlapping tours of duty on the Space Station. In order to maintain a crew of eight persons on orbit continuously during the operations phase, a manned space transportation capability (Shuttle) flight rate is required consistent with Station crew on-orbit staytimes (tours of duty). During the early stages of Station planning, a 90 day tour of duty was assumed. This was based on two factors: 1) the U.S. biomedical data base and the experience from the Skylab program indicated that NASA could provide appropriate countermeasures to permit 90 days exposure to weightlessness, and 2) programmatic requirements for keeping people in space for longer than 90 days were not in evidence. In the course of the Transportation Study, the Life Sciences Division determined that for the Space Station operations phase, extending the crew on-orbit staytimes to 180 days was feasible. As a result of the Life Sciences Division assessment (see next section), a maximum tour of duty for Space Station operations of 180 days has been baselined.

II. Space Transportation Capabilities

Space Transportation System (STS)

When the studies leading up to this report were begun, the post Challenger Space Shuttle capabilities estimates for supporting Space Station missions were as specified in a December 1986 Office of Space Flight letter to the Office of Space Station. These capabilities included performance to orbit, cargo return weight, extravehicular activity (EVA) capability and crew size. The up and down weight performance numbers were based on an STS reference configuration for Space Station east coast missions as follows: a lightweight Orbiter (OV-103, OV-104, OV-105) configured for a crew of five; a seven day mission; forward reaction control system tanks full; two space suits (no planned EVA); four cryogenic sets installed (three full); Orbital Maneuvering System propellant for rendezvous; remote manipulator system installed; and a maximum Space Shuttle Main Engine (SSME) throttle setting of 104 percent. The cargo delivery capability (ascent performance to orbit) for this configuration was 39,530 pounds to an altitude of 220 nmi for a due east launch. This performance was reduced by 8,400 pounds. with the heavier orbiter (OV-102). The cargo return capability (downweight performance) of the Space Shuttle for Space Station missions was specified as 23,797 pounds.

The baseline Shuttle EVA capability was 24 EVA man-hours per flight. For Space Station assembly missions requiring more EVA, the Shuttle could be configured to deliver up to 48 EVA man-hours with some hardware augmentation. This would require a total of seven crewmembers (four EVA crewmembers) and five EVA space suits. All EVA commitments retain a reserve for contingencies associated with the Shuttle or the Station.

The nominal crew size for STS mission planning purposes has been seven; one Shuttle mission has been flown with an eight-person crew. Based on these factors and on the potential for cross training Space Station crewmembers for certain Shuttle functions, the STS program committed to carrying up to four Space Station crewmembers on each flight.

During 1987, several studies were conducted to assess the possibility and means of enhancing the Space Shuttle's capabilities for Space Station. The analyses conducted as part of the Transportation Study supported an updated Space Shuttle commitment in the areas of performance and Space Station crew transportation support. The studies did not change the baseline Space Shuttle ascent performance commitment to Space Station, but they did serve to help define a performance improvement goal for a proposed advanced solid rocket motor, which is discussed below. Also, recently completed loads analyses allow a program decision to reduce the design load factors resulting in a significant increase in the Shuttle nominal end of mission landing weight capability. The revised landing weight limit increases the Space Station mission cargo return weight capability to 41,500 pounds, an increase of almost 18,000 pounds.

The EVA capabilities commitment remains unchanged from the December 1986 baseline. The crew size commitment is also unchanged.

A proposed Shuttle ascent performance enhancement has matured during 1987 and is proposed to provide an upgrade to the long-term safety, reliability and performance capability of the Shuttle. This enhancement would have major advantages for the Space Station as well. Subsequent to the Challenger accident, five major solid propulsion contractors were funded to study innovative design changes to improve the reliability and performance of the Shuttle solid rocket motor. The results of the studies were reported to Congress on January 16, 1987. Based on those results and an assessment of Shuttle performance needs, NASA concluded that an acquisition strategy should be directed toward the development and introduction of an advanced solid rocket motor. The resulting "Space Shuttle Solid Rocket Motor Proposed Acquisition Strategy and Plan" was submitted to Congress on March 31, 1987. The highlights of the strategy include: full and open competition among U.S. competitors; emphasis on improved quality and safety through automation and advanced manufacturing methods; and Space Shuttle ascent performance improvement.

A nine month study was initiated in August 1987 by the five propulsion contractors with a design goal of achieving 12,000 pounds increase in Shuttle payload capability (i.e., up to approximately 52,000 pounds to the Space Station orbit). The major design changes being considered to achieve such a payload increase include: thrust profile optimization; nozzle optimization; increased diameter; and reduced inert weight. All of these changes are considered low risk and a five year development program is proposed with the first flight of the advanced solid rocket motor projected for 1993.

Unmanned Launch Vehicles

At present, U.S. unmanned launch vehicles consist of an inventory of expendable launch vehicles (ELVs) and concepts for heavy-lift launch vehicles. Both the existing ELVs and the potential heavy lift launch vehicle classes have been evaluated for their acceptability and adaptability for use in the Space Station program.

A number of investigations into the use of expendable launch vehicles for Space Station assembly and operations have been conducted over the last several years. The recent Transportation Study reexamined the capabilities of the Delta, Atlas-Centaur, Titan II, Titan III and Titan IV vehicles in relation to the needs of the current Space Station revised baseline program. Considering only the mass requirements of the Space Station program, the ELV options are immediately reduced to the Titan III or IV launch vehicle configurations, since the other ELVs have a severely limited payload weight-to-orbit capability (Figure 4). The Titan III and IV vehicles can deliver between 70 and 75% of the mass to orbit capability of the Space Shuttle, which places them in a position to satisfy limited Station operational resupply requirements. Major changes would be required in Station component configurations and launch packaging, however, for these vehicles to be used effectively during the assembly phase. The shroud size of the Titan III (13 feet diameter) would severely impact major element hardware design. The Titan IV shroud can accommodate Shuttle size payloads. Both Titan III and IV would need to be modified to provide extended on-orbit support of the payload (e.g. electrical power, communications, etc.) for the several days period between arrival on orbit and final disposition of the payload. Both vehicles would also need to be equipped to safely deorbit the final stages when the delivery and payload handover is completed.

UNMANNED LAUNCH VEHICLES

TITAN II

- Performance 1,492 lbs.
  - Shroud Size 10 ft.

DELTA 3920

- Performance ~7,000 lbs.
  - Logistics Carriers 4000-6000 lbs.
  - Shroud Size 9.3 ft.

ATLAS/CENTAUR

- Performance ~11,500 lbs.
  - Shroud Size 12.0 ft.

TITAN III

- Performance ~26,000 lbs.

LIMITATIONS	ADVANTAGES
• Shroud Size 13 ft. • No Restart on 2nd Stage • Extended Duration Required on Carrier	• Available at 5/yr. Rate • Compatible with Most Logistic Element Wt. Estimates

TITAN IV

- Performance ~30,000 lbs.

LIMITATIONS	ADVANTAGES
• No Restart on 2nd Stage • Extended Duration Required on Carrier	• Compatible with NSTS Payload Bay Diameter

SHUTTLE-C

- Performance ~100,000 lbs.

ADVANTAGES

- Fully Compatible with NSTS
- Fewest Number of Launches for Assembly

NOTE: PERFORMANCE TO STATION ALTITUDE = 220 NM (28.5°)

FIGURE 4

The Titan III and IV expendable launch vehicles possess a significant mass-to-orbit capacity that could complement the Shuttle for the long-term operations program. Any shortfall in resupply deliveries that results from the finite cumulative cargo capacity of the Shuttle flights required for crew transportation could be supported by appropriate expendable launch vehicle(s).

A second category of unmanned launch systems includes the Air Force Advanced Launch System (ALS) and the Space Shuttle derived cargo vehicle (Shuttle-C). Both systems would have the payload potential to low Earth orbit of not less than 100,000 pounds. The large payload capacity of the ALS and Shuttle-C would enable the assembly of much larger segments of the Station with the dual effect of reducing the number of launches required and reducing assembly schedule time. Present plans for the ALS do not support the Space Station assembly schedule. The Shuttle-C concept on the other hand, could support Space Station assembly with a near-term, unmanned heavy lift launch capability based on existing in-place technology. The Shuttle-C concept uses the main engines, solid rocket boosters, external tank and launch facilities of the present STS, but a new expendable cargo carrier is used instead of the Orbiter. The Shuttle-C could be flight tested about four years after program authorization and begin operations the following year. Thereafter, two to three flights per year could be accommodated.

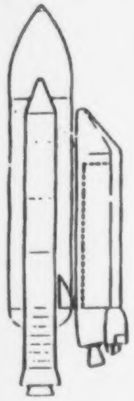
Several Shuttle-derived cargo vehicle studies have been conducted by NASA over the last 13 years and these have led to the present Shuttle-C concept. The basic guidelines and assumptions for the Shuttle-C configuration are: minimize new development and cost; maximize use of STS hardware and facilities; deliver a minimum 100,000 pounds to a Space Station orbit; and provide full interchangeability of payloads with the STS. For the Transportation Study, several Shuttle-C configurations were investigated. One of these configurations, called the "reference configuration", was used in evaluating the Space Station support scenarios discussed later in this report. The reference configuration (Figure 5) provides an additional 12 feet of usable cargo space beyond the Shuttle length of 60 feet. The added volume will accommodate an Orbital Maneuvering Vehicle for Space Station missions where rendezvous, proximity operations and docking are routinely required.

Life Sciences Support

The NASA Office of Space Sciences and Applications worked with the Office of Space Flight and the Office of Space Station during the Transportation Study to evaluate the feasibility of extending the duration of Space Station crew operations. As a result, the NASA Life Sciences Division has developed a plan to extend astronaut tours of duty aboard the Space Station up to 180 days duration to be consistent with effective management of the nation's space resources.

Space medicine studies have served to lessen many of the concerns regarding the effects of microgravity and low Earth orbit radiation on the physiology of the human space explorer. These studies have also confirmed notable physiological changes associated with U.S. spaceflights of up to 84 days duration. Of the various deleterious effects, the loss of bone mineral content, skeletal muscle atrophy, and cardiovascular deconditioning are considered to be the most medically significant.

SHUTTLE - C REFERENCE CONFIGURATION



NOMINAL 15 X 60 + 103 KLBS

- Standard 4-segment SRB's (reusable)
- Standard ET (expendable)
- Orbiter boattail (expendable)
  - -- 2 SSME's (SSME #1 omitted)
  - -- Vertical stabilizer omitted
  - -- Body flap omitted
  - -- Cap SSME #1 feedlines
  - -- OMS pods (do not install OME's, RCS tanks and 4 RCS thrusters/ POD)
  - -- RCS performs circularization and deorbit
  - -- Cover and thermally protect SSME #1 opening
- Payload carrier (expendable)
  - -- New shroud/strongback
  - -- Skin/stringer/ringframe construction
- Avionics
  - -- Uses mature design components from STS and other applications
  - -- Requires some new integration and software
- Performance (ETR) - 220 NM/28.5° - (100% SSME'S) - 103 KLBS

FIGURE 5

Some details are also known from the Soviet space program. The Soviets have shown that man can spend more than 10 months in weightlessness with a relatively high impact on crew time - MIR crews spend 2 hours per person per day on exercise and related countermeasures. Additionally, they apparently require an extended period of post-flight rehabilitation to restore muscle condition. These and other effects of long duration space flight must be assessed and countermeasures developed.

Investigations to certify routine stays of up to 180 days on the Space Station will require that procedures for crew health maintenance be developed in a timely fashion. Those investigations were defined in a preliminary way in September 1987 and will be defined to a high degree of specificity by the summer of 1988. Based on the current state of knowledge, there is justification for NASA life scientists to develop a sophisticated capability for medical investigations to enable missions of 180 days and longer. The life sciences technology will be operationally tested during the Space Station era. With an augmented space medicine program, it is expected that the Life Sciences program, both ground and flight, will lead to routine long duration crew operations as early as the second year of Space Station operations.

III. Space Station Transportation Alternatives

The 1986 baseline assembly and operations plan for the Space Station stipulated a commitment of 8 Shuttle flights per year on a sustained basis. Recognizing the demand such a flight rate would place on the Shuttle fleet, the Transportation Study was performed in 1987 in part to evaluate how the Space Station could be safely assembled and efficiently operated at a reduced flight rate. The study defined Space Station transportation options, including the use of unmanned launch vehicles and an improved Shuttle with greater lift capability. One constraint imposed on the study was the condition that no changes would be made to accommodate other transportation modes which would render a Station element incapable of being launched by the baseline Shuttle. In the course of deriving feasible assembly sequences, attention was given to the issue of maintainability and the ability to cope with potential launch or equipment failures that could delay rendezvous with the partially assembled Station.

The initial analysis indicated that current expendable launch vehicles, even those of the Titan IV class, were not useful in the baseline assembly process due to their performance limitations. Future unmanned launch vehicles with capabilities comparable to, or greater than, the Shuttle would be useful, however. The only vehicle of the heavy lift class that was assessed to be capable of being developed in time to participate in the Space Station manned base assembly sequence was a Shuttle derived cargo vehicle, named the Shuttle-C. However, current expendable launch vehicles of the Titan class could be used for operations resupply support after Space Station assembly is complete. A detailed study of the Space Station hardware and operations changes required to accommodate expendable launch vehicles will be undertaken this year. The study will consider government-owned and commercially provided launch vehicle services.

Space Station Assembly Phase

The baseline Space Station assembly sequence was developed using the baseline Shuttle without improvements and, initially, resulted in a 18 flight scenario. A reduced Shuttle performance projection following the Challenger accident gave rise to a consideration to compensate for the reduction by assembling the Space Station at a lower altitude. The idea was discarded because the orbital decay time was so short at the lower altitude that, in the event of a Station propulsion system failure, a launch package could be lost before another Shuttle was launched for a rescue operation. The assembly concept was reexamined to see how the baseline Shuttle could assemble the Space Station at the design altitude. It was decided to defer the delivery of the nodes to the third assembly flight, and incorporate an avionics package in lieu of the nodes. These changes would reduce the weight of the first two launch packages, making it possible to put them into a higher orbit with an acceptable orbital decay time. This new assembly concept was achieved by adding one flight to the assembly sequence.

Baseline Shuttle. Using the currently baselined Shuttle, 19 flights are now required for Space Station assembly (Figure 2). This 19 flight scenario is determined by the Shuttle's lift capability and payload bay volume, and by the required sequence of Station component assembly to assure a self-sustaining spacecraft in orbit. Each launch package design may use the full Shuttle payload bay volume. The weight of each launch package includes a 10% margin built into all weight estimates plus a 2,000 pounds Space Station Program Director's reserve. Additional weight margin will be applied in the first three launch packages to insure fully installed, redundant systems. These three packages will be launched to an altitude which will provide seven to ten months to recover from any unexpected difficulties that may be encountered in the early assembly phase. The remaining 16 flights will be delivered to the design rendezvous altitude. Preflight preparation of each launch package, including prelaunch processing at the Kennedy Space Center in parallel with other Shuttle payloads, results in an assembly sequence of 36 months duration. The total transportation cost for the baseline Shuttle assembly sequence is estimated at $1.0 billion.

The following is a description of the three options considered for Space Station transportation and assembly. These options were evaluated using margin, safety, redundancy, and burden on the Shuttle fleet as discriminators. They were compared against the baseline assembly sequence described above.

Enhanced Shuttle Option. An examination was conducted to see how an enhanced Shuttle with up to 12,000 pounds greater ascent performance capability using advanced solid rocket motors would affect the assembly sequence. The enhanced Shuttle was found to approach the optimum mix of volume, weight and EVA capability. It reduced the number of Shuttle flights needed for assembly from 19 to 14 (Figure 6). This assembly sequence scenario allows increased ground integration of such elements as the power modules, propellant tankage, and aft resources nodes; permits launch of the laboratory module with increased initial capability; allows a 30% reduction in EVA man hours; and provides increased weight margin on most flights. The transportation cost of the enhanced Shuttle option is estimated at $.8 billion.

ENHANCED SHUTTLE
ASSEMBLY SCHEDULE COMPARISON

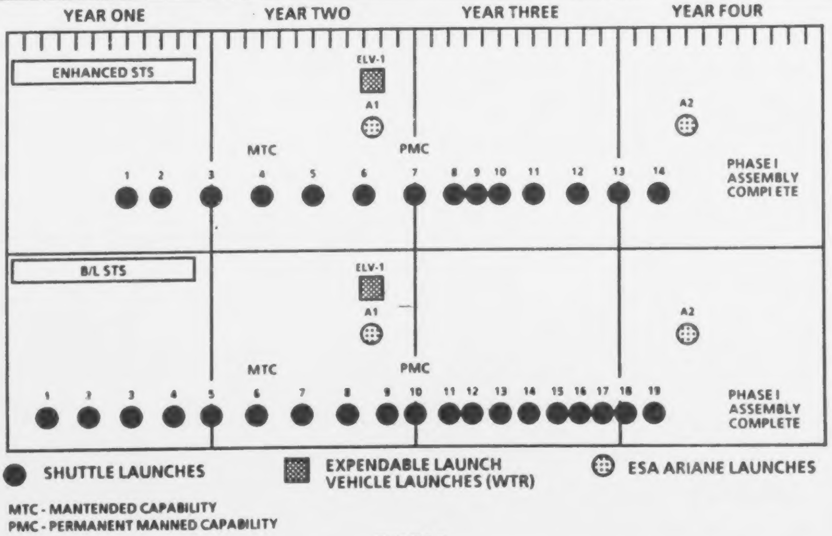


FIGURE 6

Shuttle-C/Baseline Shuttle Option. An analysis was conducted to assess the effect of utilizing a Shuttle-C in addition to the baseline Shuttle in assembling the Space Station. The resulting scenario (Figure 7) reduces the total launch requirements from 19 flights to 12. The 12 flights would be composed of seven Shuttle flights and five Shuttle-C flights. The heavy lift launch capability afforded by the Shuttle-C permits launch of the laboratory with all planned experiments installed; allows a 40% reduction in planned EVA; and permits even greater ground integration on such elements as the aft nodes and airlocks, propellant tankage and forward nodes. The Shuttle payload margin remains equivalent to the baseline scenario.

Preflight processing analyses would project assembly time reduction from 36 months to 19 months. The transportation cost of this Shuttle-C and baseline Shuttle option is estimated at $2.1 billion.

SHUTTLE-C/BASELINE SHUTTLE
ASSEMBLY SCHEDULE COMPARISON

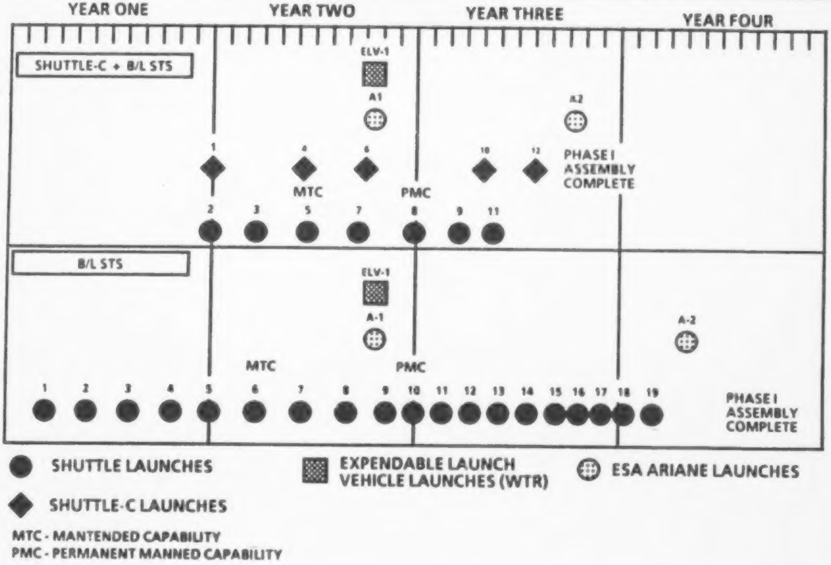


FIGURE 7

Shuttle-C/Enhanced Shuttle Option. Finally, the combination of a Shuttle-C and an enhanced Shuttle was examined. The Shuttle-C/enhanced Shuttle scenario (Figure 8) reduces the total launch requirements from 19 flights to 11, composed of seven Shuttle flights and four Shuttle-C flights. It also permits launching the laboratory with all planned experiments installed; allows a 40% reduction in planned EVA; and a further increase in ground integration of the items mentioned in the previous scenario, as well as the entire propulsion assembly, and the Japanese laboratory and its external facilities. The Shuttle performance margin is equivalent to the enhanced Shuttle scenario. Preflight processing analysis projects an assembly time reduction from 36 months to 16 months. The transportation cost of the Shuttle-C/enhanced Shuttle option is estimated at $1.8 billion.

SHUTTLE-C/ENHANCED SHUTTLE
ASSEMBLY SCHEDULE COMPARISON

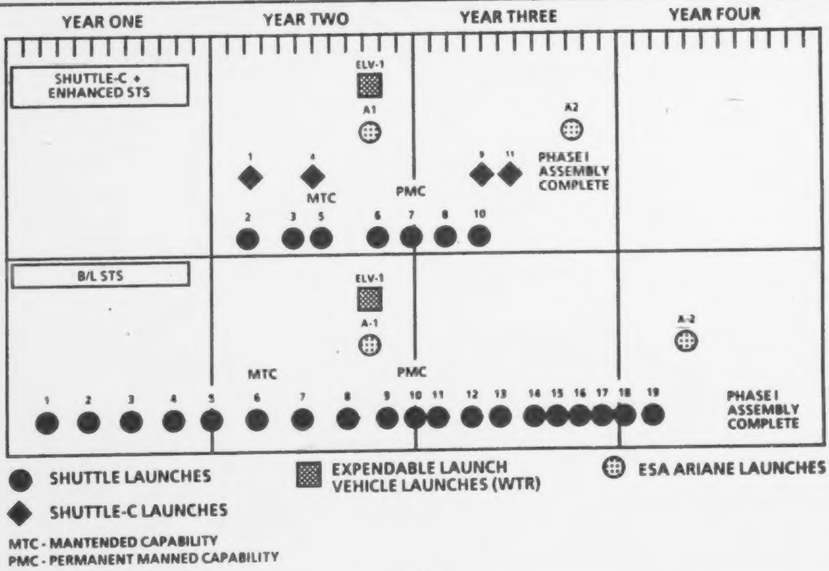


FIGURE 8

Space Station Operations Phase

Transportation support for the Space Station manned base operations period involves three major considerations. The first two considerations are annual up-mass and down-mass requirements to support the manned base housekeeping functions and Station users' needs. As was shown in Section I, the annual operations requirements for the Station and its users is estimated at 180,000 pounds up-mass and 156,000 pounds down-mass. Using the baseline Shuttle capabilities estimates and cargo manifesting constraints, it would take five Shuttle flights to accommodate the presently projected up-mass.

At the outset of the Transportation Study, there was a concern as to whether there was sufficient Shuttle down-mass capability to sustain the Space Station. While expendable launch vehicles could be considered for resupply operations where a Shuttle shortfall might exist, those vehicles have no cargo return capability. Therefore, the original Shuttle commitment of a down-mass return capability of 24,000 pounds per flight was insufficient and would have necessitated the development of an alternate means of returning materials to Earth. However, the recently revised commitment of a down-mass allowance using the baseline Shuttle of 41,500 pounds provides the capacity required to support the Space Station needs. In fact, the combined capability of five Shuttle flights provides a down-mass margin of 30,000 pounds per year over Space Station requirements.

The third major consideration is crew rotation. The Space Station crew rotation requirements derive from the crew complement, crew delivery capability and crew staytime on orbit. The baseline Space Station complement begins with a crew of four and grows to eight in about one year. The Shuttle provides a delivery and return capability of four Space Station crew members. The Space Station crew staytime baseline at the beginning of the Transportation Study was 90 days, which resulted in eight Shuttle flights per year required for crew rotation purposes alone. The new baseline achieves 180 days by the time the crew complement reaches eight. This crew rotation strategy can be supported by the five Shuttle flights per year derived from the down-mass requirements. The five flights, in fact, provide a margin that will permit tours of duty shorter than 180 days, staggered tours or unscheduled crew rotations.

Since there is presently no means other than the Shuttle for routine return of material from space, and since accommodating the down-mass requirements more than adequately supports the crew rotation strategy, it was concluded that Space Station operational requirements could be satisfied with five Shuttle flights per year. Any potential operational up-mass shortfall could be eliminated by balanced Space Station operational planning and reduced carrier weights to stay within Shuttle capabilities or by the use of an enhanced Shuttle or an appropriate unmanned launch vehicle. It should be noted, however, that the use of unmanned launch vehicles to deliver operational supplies and equipment to the Space Station will require some changes in the program. These changes include a dedicated Orbital Maneuvering Vehicle; the development of dual compatible logistics carriers; and the possible need for an alternative trash disposal system.

Risk of Capital Loss

The Transportation Study included an analysis of the risk of loss of capital assets during the launch and assembly of the Space Station and a strategy for mitigating program impacts of such a loss. This analysis concentrated on the definition of a strategy that would reduce, to an acceptable level, the effect of the loss of major program hardware.

All major elements and equipment through man-tended capability will be protected from major schedule delay through the reprogramming of pipeline spares, and the selection and phasing of operational spares. Pipeline spares are those assemblies and equipment intended for later launch which are similar to, or are identical to items currently being launched. Operational spares are those hardware items which are intended to replace equipment which fails during the normal course of operations. Elements and equipment launched from man-tended capability through permanently manned capability will be protected from extreme schedule delay by the selection and phasing of operational spares and the remanufacture of major elements using long-lead assembly spares. Long lead assembly spares are those components of major assemblies which require the longest time to manufacture. This strategy will maximize the use of existing spares inventories and minimize the cost of capital loss risk management.

IV. Cost Implications

The transportation options described above for assembly of the Space Station manned base have been compared for cost-effectiveness. Estimates for the proposed advanced solid rocket motor (ASRM) and the Shuttle-derived vehicle (Shuttle-C) are of a preliminary nature, since they are now in the definition study phase. Using the preliminary estimates and comparing only launch costs, the marginal launch costs of the enhanced Space Shuttle with ASRMs enable the manned base to be assembled at a lower total transportation cost than either the baseline Shuttle or the combination of the Shuttle and Shuttle-C. The advantage of the enhanced Shuttle is a direct reduction in the number of Shuttle flights. Although a further reduction in the number of Shuttle flights is possible with the Shuttle-C, this advantage is offset by the additional costs associated with the largely expendable character of that vehicle. Due to the reduction in the number of Shuttle flights, both the Shuttle and the combination of the Shuttle-C and Shuttle could enable the assembly process to be completed earlier; however, potential savings that might result from an earlier completion have not been reflected in this report.

The cost estimates that follow are based on the analyses done by NASA during the Transportation Study. The launch cost comparison does not include the development costs for the ASRM or the Shuttle-C since both developments have mission applications beyond the Space Station. Assembly of the Space Station can be accomplished with the baseline Shuttle, and does not require either capability.

In all transportation options, the assembly of the Station manned base requires some number of Space Shuttle flights. Use of the Space Shuttle incurs common costs for the development of Shuttle-to-Station interfaces. These developments include a docking system, Station crew accommodations (e.g., seats) in the Orbiter, water/power transfer, and use of the Orbiter remote manipulator system. The resulting common costs are estimated at approximately $150 million in FY 1988 dollars. The Space Shuttle marginal cost, i.e., the variable cost per flight where there is an existing operations base, was used in this analysis. The marginal cost is composed of propellants, the expendable external tank, consumable items (such as pyrotechnic devices), and flight-rate related spares. This marginal cost is approximately $44 million per flight in FY 1988 dollars.

Baseline Shuttle. Using the baseline Space Shuttle performance, the estimated Space Shuttle transportation cost for the 19 Shuttle assembly flights of the manned base is $.8 billion in FY 1988 dollars. This does not reflect offsetting reimbursements for the several launches required for the hardware being furnished by the international partners. It is assumed that the U.S. platform will be launched on an expendable launch vehicle and that the European Space Agency will launch its polar platform and man-tended free flyer with Ariane. Including the previously addressed common Shuttle interface costs ($150 million), the resultant baseline transportation cost totals $1.0 billion.

Enhanced Shuttle Option. In the Advanced Solid Rocket Motor (ASRM) option, it is assumed that the flight hardware will have an equivalent reusable life compared to the present SRM and there will be no change in the expendables cost (predominantly propellants) and resultant marginal cost. Based on its estimated additional payload delivery capability and the reduction from 19 to 14 Shuttle flights, the effect of the Shuttle/ASRM option is a reduction in assembly transportation costs from the baseline, for a total of $.8 billion in FY 1988 dollars.

Shuttle-C/Baseline Shuttle Option. The use of common elements with the STS enables the cost of those elements to be priced at the marginal rate, e.g., the additive costs for hardware where the existing operating infrastructure covers the basic support costs. At the launch site, the existing base support and Shuttle processing workforce would be supplemented by personnel required for facilities, equipment, and software unique to Shuttle-C. An estimated recurring marginal launch cost of approximately $.3 billion in 1988 dollars is utilized for this analysis. Use of the Shuttle-C for manned base assembly may also involve a second Orbital Maneuvering Vehicle and operational support--estimated at $150 million.

Using the combination of the baseline Shuttle performance and the Shuttle-C, the transportation cost for assembly of the manned base is derived by assuming five Shuttle-C launches at a marginal cost of $.3 billion each and seven Shuttle launches at a marginal cost of $44 million each. The sum of the two factors is $1.8 billion in 1988 dollars. Adding the common Shuttle interface development costs ($150 million) and the unique costs ($150 million), the total cost for this option is estimated at $2.1 billion in 1988 dollars.

Shuttle-C/Enhanced Shuttle Option. The option of combining the Shuttle/ASRM with the Shuttle-C reduces Shuttle-C launches by one. The resultant total cost for this option is $1.8 billion in 1988 dollars.

Space Station Operations. With regard to the recurring cost to operate and maintain the manned base, the baseline of five Space Shuttle flights per year projected to meet both crew rotation and upweight/downweight payload (experiment and logistics) requirements results in an estimated annual transportation cost of $220 million in 1988 dollars.

V. Conclusion

The current Space Station program assembly and operations planning is designed for the existing Space Shuttle transportation capability. Such planning eliminates the uncertainties associated with a development effort. In addition, if the advanced solid rocket motor is approved, it will be of significant benefit in providing additional payload weight capabilities and margins with decreased transportation costs. If an early national heavy lift launch vehicle capability is developed, it would be used in conjunction with the Shuttle for Space Station assembly. The launch costs of using a heavy lift capability may be greater than with the Shuttle alone. While it has been shown that the Space Shuttle is uniquely suited for the assembly and operations requirements of the Space Station program, it is also recognized that some of the existing expendable launch vehicles are suited to satisfy limited Station operations requirements. It is anticipated that they will be used in supporting the long-term Space Station operations phase.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

FEB 18 1988

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

This letter is in response to the requirement in Section 119 of Public Law 100-147, the NASA Authorization Act of 1988, that I review the report of the National Commission on Space and submit a recommendation for a long-range implementation plan thereof.

As you know, the National Commission on Space has outlined a profoundly ambitious civil space program that calls for powerful parallel emphases on space science, exploration, and industrialization supported by a broad base of advancing technologies and of sequentially-deployed new operating space systems. The Commission, looking to the early part of the next century, recommends major centers of activity in both low and high Earth orbit, on the Moon, on Mars, and in deep space. The Commission integrates these different arenas of activity into a continuing program of expansion on all fronts. There are no dead-ends in its planning: the highly rewarding fields of space science, applications, and technology are recommended for pursuit, as are more dramatic and visible elements like human settlements on the Moon and operations on the Martian surface. The Commission estimates that the program it advocates would require a smaller percentage of the gross national product than was committed to Apollo in the 'sixties; its absolute cost estimates are nonetheless large, reaching over $20 billion per year in current dollars by the end of the century.

The Commission's inspiring vision of what America could do in space in the 21st century articulates graphically long-term goals and expectations that have always been implicit in the United States civil space program. The report parallels NASA's planning in many respects. We both recognize the importance of combining strong continuing programs in space science, applications, technology, and commercialization with step-by-step movements outward into space with manned systems, as in the case of the Space Shuttle and the Space Station. We also agree on the importance of greater involvement of the private sector and of reducing the cost of space transportation. The report also parallels NASA's thinking in emphasizing the crucial importance of a sustained national commitment backed by adequate and stable budgetary support for achieving long-term goals in space.

The Commission's report, however, lays out only a generalized overall schedule of major technical milestones. It shows the interrelations of the recommended space transportation improvements to the capabilities required for permanent remote operations and human planetary exploration, but understandably falls far short of the degree of detail needed for program planning and reliable cost estimates. Moreover, since the major build-up in space contemplated in the Commission's planning would not occur until the 1990's, the Commission could presume that by that time the Nation's current budget and deficit problems would be sufficiently resolved to permit the Nation to undertake the proposed major new initiatives in space. The essential connection between present realities and the recommended national commitment to the space frontier are not addressed in detail.

An implementation plan for the Commission's report must face squarely both of these facets of the problem: it must be based on a deeper understanding of the technical problems and options, and it must bridge the gap from where we are today to where we have to be to start to realize the Commission's vision. Such a bridge cannot be built simply by elaborating a plan of specific activities that begin now and purport to lead inevitably to a predetermined future. Any such implementation plan would presume knowledge we do not have, decisions that have not been made, and technologies that do not exist. Each step between the present and the ambitious vision of the National Commission's report must build on the experience of its predecessors.

It is now the formal policy of this Administration that the United States will move forward and outward to expand the human presence beyond Earth and into the solar system. It is not clear today, however, which specific means and directions will serve the Nation best. It may very well be that this movement will follow the programmatic lines and schedules developed by the National Commission. It is also possible that some different ordering of targeted capabilities and acheivements will better reflect the national will and priorities a few years from now. I am, therefore, not ready to recommend a long-range implementation plan for the particular structure laid out in the Commission's report or for any alternative single-sequence master plan.

I am prepared, on the other hand, to recommend, as the necessary first step in such an implementation plan, the measures that should be taken over the next few years to move in the direction the Commission envisions. We must devote as much time and resources as necessary to advancing all relevant technologies on the broadest front so as to have in-hand substantial assurance of success when we target, as a Nation, a particular space challenge as the next goal in our evolution to a spacefaring society. We need knowledge; we need experience in Earth orbit of the sort our planned Shuttle and Space Station activities will bring us; we need to understand in-depth our technical options; we need management skills and tools that permit meaningful cost estimates to be made and actual costs to be controlled; we need advanced studies and conceptual engineering breakthroughs; we need a flow of new technical solutions to replenish a technical reservoir nearly dry from neglect. We need to get ready for whatever future decision makers may demand of us, and, in itself, this is a larger challenge than those we have met and overcome to date.

Specifically, I recommend that NASA should and should be enabled to:

1. Maintain, through the current period of budgetary austerity, a strong, and yet fiscally responsible civil space program including not only full recovery of Space Shuttle and ELV capabilities and development of the Space Station but also forward-looking programs in space science and the advancement of space technology. This core program is the essential platform on which implementation of future long-term goals in space must be based.

2. Mount a multi-year effort to study in-depth the technology requirements and program options for future human exploration of the solar system. Such studies are now getting underway in NASA'S new Office of Exploration, building on the ideas in the Commission's report and the options identified in the recent report by Dr. Sally K. Ride, "Leadership and America's Future in Space." Much more work is needed before we can be in a position to identify specific program plans and options and make reliable estimates of the schedules and costs involved.

3. Initiate, with $100 million in the FY 1989 budget, a systematic development of technologies necessary to enable and support a range of future manned and unmanned missions. This technology program -- Pathfinder -- will be oriented toward a future Presidential decision on a focused program of manned and unmanned exploration of the solar system.

Thus, I foresee a period of several years in which the U.S. must consolidate its civil space activities, must concentrate on successful execution of approved programs, while building up the level of effort across the enabling technologies and must refine the rationale for the next family of space initiatives that I believe will inevitably become part of the national agenda. We must have a basis of choice so strong and broad as to assure that the challenge chosen is understood and that the country is competent to pursue it.

The President has reinforced the above three components of the Nation's civilian space program as fundamental for providing a sound basis for future decisions on moving toward the recommended goal of expanding the human presence in space. However, I believe it would be premature and presumptuous to attempt to project either a temporal or financial envelope for this effort until we are much further along in the process of substantive research, analysis, and advanced mission studies. You may be assured that this process will be carefully directed at the goal of giving decision makers in the Executive Branch and Congress the opportunity to give full consideration to the opportunities, values, risks, and costs of human exploration of the solar system.

Sincerely,

James C. Fletcher

James C. Fletcher
Administrator

cc: Honorable Manuel Lujan, Jr.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

March 14, 1988

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed is "Satellite Servicing, A Report to Congress" in response to H.R. 2782, Section 118, of the National Aeronautics and Space Administration Authorization Act of 1988 which requested that NASA conduct a thorough and comprehensive study of satellite servicing with a view toward establishing national goals and objectives for utilizing such capabilities.

Satellite servicing is an evolving technological activity in its early phase of development. NASA on-orbit experience, ranging from initial attempts to service early in the manned space program to present day planning, provides the basis for planning future capability. The first Extravehicular Activity occurred during Gemini IV in 1965. Human interaction with on-board experiments was an essential ingredient in the success of the Skylab missions. More recently, the use of the Shuttle for the solar maximum repair mission, the successful recovery of Palapa and Westar, and the successful repair of SYNCOM IV-3 has established on-orbit satellite servicing as a viable capability. Human interaction with on-board experiments, including on-orbit repairs, has increased with Spacelab missions.

The current NASA servicing capability is Shuttle-based, using the remote manipulator system and extravehicular activity. These capabilities are critical to realization of the long-lived science observatories and to Space Station operations. Plans for Space Station-based servicing are evolving. Servicing support equipment, tools, and aids, in addition to servicing support systems currently in development, have evolved from prior experience. Today, man is critical to achievement of servicing objectives; future development of telerobotic and robotic servicing capabilities will evolve to meet user needs.

The enclosed report reviews NASA's satellite servicing experience to date; servicing systems which exist, which are under development, and which are planned; spacecraft design considerations; satellite servicing requirements; coordination of NASA's satellite servicing activities; impacts on insurance; and pricing. NASA goals and objectives for the utilization of satellite servicing capabilities are presented as candidates for national civil goals and objectives.

Sincerely,

James C. Fletcher
Administrator

Enclosure

cc: Honorable Manuel Lujan, Jr.

SATELLITE SERVICING

A NASA REPORT TO CONGRESS

NASA OFFICE OF SPACE FLIGHT

WASHINGTON, D.C.

MARCH 1, 1988

Preface

Satellite Servicing, A Report to Congress has been compiled by the National Aeronautics and Space Administration in response to a request from the Congress to *"... conduct a thorough and comprehensive study of satellite servicing with a view toward establishing national goals and objectives for utilizing such capabilities."* Section 118 of the National Aeronautics and Space Administration Authorization Act of 1988 (H.R. 2782) stipulates that *"... the capital investment in space satellites and vehicles should be enhanced and protected by establishing a system of servicing, rehabilitation, and repair capabilities in orbit (hereinafter referred to as 'satellite servicing')."*

Satellite Servicing is recognized within NASA as an evolving capability currently in an early stage of development, a fact reflected in the compilation of this document. With this understanding, NASA addresses those major elements of the Act identified in the Congressional Request. The seven elements are listed below in the order in which they appear in the report.

- *Experience to date with on-orbit satellite servicing including the costs of such operations and the fees charged to non-NASA users;*
- *The use of the Shuttle, the Station, and other space vehicles to carry out or support satellite servicing;*
- *The pertinence of satellite servicing to satellite and vehicle design;*
- *The pertinence of satellite servicing to NASA and other space programs, including science and applications programs;*

- *All potential users of satellite servicing capabilities, including civilian, defense, private, and foreign satellites and space vehicles;*

- *The pertinence of satellite servicing to insurance, including the character, cost, and availability of insurance; and*

- *The prices to be charged for satellite servicing such that the full costs of such servicing can be recovered.*

NASA intends that this report shall inform the reader as completely and comprehensively as possible regarding the current scope of satellite servicing, provide definitive examples of capability, and address future requirements. Within this context, overall NASA goals and objectives for the utilization of satellite servicing capabilities are presented as candidates for national civil goals and objectives.

Acknowledgement

NASA's Office of Space Flight gratefully acknowledges the assistance of the NASA Satellite Servicing Steering Committee and Working Groups' representatives (the Office of the Comptroller, Space Science and Applications, Aeronautics and Space Technology, Space Station, Commercial Programs, External Relations, Exploration, and Space Operations), in addition to other members of the NASA staff who have contributed significantly to this report.

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Executive Summary

Satellite servicing is an evolving technological activity currently in the early stages of development. NASA on-orbit experience, ranging from initial attempts to service early in the manned space program to present day planning, provides the data for future capability.

o The first EVA occurred during Gemini IV in June 1965; Apollo missions further extended EVA and IVA experience. Human participation in the execution of onboard experiments was an essential ingredient in the success of Skylab Missions. With the advent of the Space Transportation System, major advances in on-orbit servicing of spacecraft were demonstrated. Solar Maximum Mission and successful recovery of orbiting commercial satellites have established on-orbit satellite servicing.

o The Satellite servicing base today includes the existing Space Transportation System and the planned Space Station. Servicing support equipment, tools, and aids, in addition to servicing support systems currently in development, have evolved from prior experience. Future development of telerobotic and robotic servicing capabilities (e.g., Flight Telerobotic Servicer) will evolve to meet user needs.

o Space Station and scientific and commercial materials processing programs cannot exist without servicing as an enabling activity. Major science programs, including Hubble Space Telescope, Earth Observing Systems, and others, plan to achieve extended operational lifetimes and mission flexibility through the use of on-orbit servicing. The NASA Office of Space Science and Applications (OSSA) is planning to use on-orbit servicing to benefit its key programs, for example, the Great Observatories: Hubble Space Telescope; Gamma Ray Observatory; Advanced X-Ray Astrophysics Facility; and Space Infra-Red Telescope Facility; and the Explorer Program. The importance of planning for servicing in the early stages of program definition development is recognized as essential. Modularization and reliability factors are important to reduce life cycle cost of spacecraft.

- *An initial DoD study (the Space Assembly, Maintenance and Servicing Study--SAMSS) has not yet identified near-term military satellite servicing requirements. NASA continues to work closely with the DoD in the area of satellite servicing through a Memorandum of Agreement.*

- *Availability of on-orbit satellite servicing may contribute to lower insurance coverage rates for commercial spacecraft. However, U.S. Government payloads are not impacted by insurance charges.*

- *NASA pricing policies established in 1985 are now under review as a result of changes to NASA operations.*

- *NASA proposes that utilizing satellite servicing enhances the maintenance and upgrading of national investments in space systems.*

Satellite Servicing Terminology

For purposes of clarity in meaning, satellite servicing is defined as any activity performed on orbit to assemble, maintain, repair, resupply, upgrade, deploy, retrieve or return various spacecraft and/or facilities. To assist the reader with an understanding of these terms, each function is defined as follows:

(1) Assemble: join elements to form entities such as antennas, platforms, and spacecraft.

(2) Maintain: perform activities required for continuation of system performance at an acceptable level.

(3) Repair: return failed or degraded units to acceptable operation.

(4) Resupply: replenish consumables such as cryogens, propellants, other fluids, and raw materials.

(5) Upgrade: replace payload instruments or spacecraft bus subsystems with hardware of greater capability.

(6) Deploy: (a) release and provide initial separation distance, or (b) unfold/extend an appendage or long structure.

(7) Retrieve: rendezvous, capture, and stow.

(8) Return: transport from retrieval point back to a base such as Space Station or Earth's surface.

A number of commonly used acronyms and terms referred to throughout the document are also defined below:

EVA - extravehicular activity: Operations performed by crew members wearing space suits outside a habitable environment.

IVA - intravehicular activity: Operations performed by crew members within a habitable environment.

MMU - manned maneuvering unit: a multipurpose astronaut mobility unit allowing short-range free flights.

RMS - remote manipulator system: a 55 foot teleoperated arm on the STS for spacecraft deployment and proximity manipulation.

OMV - orbital maneuvering vehicle: A propulsion stage now in development that will be capable of transporting payloads between low Earth orbits and performing a number of different missions. The OMV is a reusable vehicle capable of being deployed from the Space Shuttle. Alternatively, the OMV may be based at the Space Station for deployment to retrieve accessible spacecraft and return them to the Space Station for refurbishment and reuse.

OTV - orbital transfer vehicle: A potential propulsion stage that will be capable of transporting payloads from low Earth orbits to higher energy orbits including the geostationary transfer ellipse and earth escape trajectories. The OTV is planned as a reusable vehicle capable of being deployed from the Space Shuttle and retrieved, or (alternatively) based at the Space Station for subsequent refurbishment and reuse.

Spacecraft/Satellite - The combination of mission equipment and carrier spacecraft capable of autonomous operation in space.

Introduction

On-orbit Satellite Servicing is a capability in an early stage of evolution. To date, such servicing has been entirely dependent on the presence and support of humans in space. Dependence on man has allowed great flexibility in the servicing tasks attempted since human beings are inherently inventive and dexterous. However, it has also severely limited the number of programs that have used or can use such a capability, since such programs must be associated with, or have the capability to achieve, a close proximity with the manned space vehicle.

Activities that are now acknowledged as essential elements of satellite servicing have been present in various forms since the early days of the Gemini program. The technologies of docking, assembly, remote manipulation, and Extravehicular Activity (EVA) which are an integral part of NASA's current servicing capability were first developed to support the operational needs of the manned space program. Early servicing activities, (for example, the replacement of the Skylab sun shield) were, in fact, undertaken as a necessary part of the program, rather than as a deliberate demonstration of on-orbit servicing. The many instances of on-orbit servicing performed on a more widely defined and less visible basis, however, also merit attention. Intravehicular activity (IVA), manned activity which takes place in orbit specifically to maintain, repair, and upgrade internal spacecraft equipment is an example of low visibility servicing (e.g., recalibration, diagnosis and fault isolation, assembly and checkout of new equipment).

On-orbit servicing activities already demonstrated have proven both the technological feasibility and potential of servicing for certain applications. For example, the Solar Maximum Mission (SMM) and Syncom IV-3 repair missions provided a technological and experience base for planning the long-term on-orbit maintenance of other NASA free-flying spacecraft, including Hubble Space Telescope. The success of on-orbit assembly of EASE/ ACCESS on STS flight 61-B demonstrates the enabling capability of satellite servicing for construction of Space Station. The Station must also be maintained on-orbit in order to function as a permanently manned base. Servicing has been, and will remain, a vital ingredient of NASA's microgravity life sciences and materials sciences research programs and will be required to support the commercial ventures which may evolve from these programs.

"Classification of Servicing Activities" (Fig. 1) summarizes this discussion of past and future servicing efforts. Up to the present time, on-orbit servicing activities have occurred primarily as a by-product of other ventures, or as (very successful) feasibility experiments. In the future, some servicing activities will be essential as program enabling for on-orbit spacecraft evolution.

On-orbit servicing, however, has not yet proven to be applicable to a wide range of programs for a number of reasons. Programmatic implications, scientific and technical ramifications, and cost impacts associated with such a course of action are extremely complex. Tradeoffs will be required in satellite and payload design, orbit selection, science or applications data return, operational complexity, ground support, flight support, space transportation and on-orbit manned support and facilities. Advanced space technology development in automation and robotics, aeroassisted return from geostationary orbit, autonomous rendezvous and docking, in-space assembly and construction, and cryogenic fluid management may significantly expand the range of missions that can benefit from on-orbit servicing.

NASA is currently engaged in several pioneering ventures to better determine the programmatic benefits and costs associated with satellite servicing from the user viewpoint. The first experiment of this nature was the SMM repair mission. Upon repair completion, six of seven instruments were operational and the planned spacecraft operational life of three years was tripled to nine years. The restored spacecraft has provided invaluable data on non-solar subjects, e.g., a gamma-ray emission from outside our solar system, supernova SN 1987a, and ozone concentrations in the atmosphere. Two other Astrophysics Division free flyers which will provide invaluable information on program benefits and user support costs

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CLASSIFICATION OF SERVICING ACTIVITIES

ACTIVITY / TIMEFRAME	PRIOR TO 1987	BEYOND 1987
Servicing as a by-product of the manned space program	GEMINI EVA APOLLO SKYLAB SPACELAB	▨
On-orbit servicing experiments to demonstrate feasibility	SMM REPAIR SYNCOM IV-3 WESTAR PALAPA	▨
Required on-orbit servicing	▨	U.S. LIFE SCIENCES FACILITY U.S. MICROGRAVITY FACILITY SS ASSEMBLY/RESUPPLY MULTIDISCIPLINARY ATTACHED PAYLOADS LDEF RETRIEVAL GREAT OBSERVATORIES EXPLORER PLATFORM
Optional on-orbit servicing	▨	FREE FLYERS PLATFORMS

Figure 1

associated with the long term maintenance of unique systems are the Hubble Space Telescope and the Gamma Ray Observatory. (A report on the maintenance and refurbishment program planned for the Hubble Space Telescope was provided to Congress by NASA in 1986). In addition, the U.S. life science and materials science research facilities, planned for flight on the Space Station, should provide additional insight into the optimum levels of reliability, modularity, and serviceability in a manned and man-tended operating environment.

For on-orbit servicing to be cost-effective, a wide variety of cost factors, including life-cycle cost, must be taken into consideration (see Chapter 4). In addition to the basic costs of space transportation and manned support for servicing activities, users must consider flight systems and the ground logistics costs. This may include spares, tools, support equipment, test equipment, documentation, and sustaining engineering costs. Such considerations place importance on controlling developmental costs of repeatedly used items and lead to increased consideration of standard spacecraft, systems or subsystems, and interfaces. NASA is working toward commonality at the system and subsystem level.

Because of the dependence on manned servicing support, only those payloads which fly in inclinations and at altitudes accessible from the STS or the Space Station can currently be serviced. Alternate, non-manned, servicing capabilities will be required for servicing missions to be initiated from Expendable Launch Vehicles (ELV's) and to be conducted remotely at spacecraft in polar or geosynchronous orbits, or other orbital inclinations. NASA is conducting enabling research for such remote servicing activities by developing and utilizing telerobotic servicers for the STS and Space Station. Assuring different methods and approaches for such remote servicing is part of the Earth Observing System (EOS) Phase B study activities.

Since on-orbit servicing depends on program specific factors such as program objectives and orbit accessibility, decisions to plan for on-orbit servicing are made on a program by program basis. For those programs which do utilize on-orbit servicing, however, a servicing infrastructure is needed in order to exploit potential benefits.

In conjunction with a desire to share its extensive expertise in the application and utilization of on-orbit servicing, NASA is supportive not only of the servicing needs of NASA users, but also those of the DoD, domestic commercial, and foreign users. The commercial Industrial Space Facility (ISF) and ESA's Eureca are examples of commercial and foreign spacecraft that are being designed to utilize NASA servicing capability. Although the initial phase of the joint study with the USAF (the Space Assembly, Maintenance and Servicing Study--SAMSS) has not identified near-term military satellite servicing requirements, NASA continues to work closely with the DoD in the area of satellite servicing. This joint effort takes place through a Memorandum of Agreement designed to address on-orbit maintenance and repair.*

In the remainder of this report, each of the seven elements identified in the Preface is discussed as follows. Chapter 1 describes the experience to date with on-orbit servicing, from Gemini to the present. Chapter 2 addresses the use of the STS, Space Station, and other vehicles to support satellite servicing by describing current capabilities, considerations, and development activities for on-orbit servicing support. Chapter 3 provides a discussion of the pertinence of satellite servicing to satellite and vehicle design, while Chapter 4 discusses the pertinence to space programs in general. Chapter 5 addresses the coordination of current activities among the various users of servicing capabilities, including civilian, defense, private, and foreign communities.

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*A Memorandum of Agreement (MOA) between NASA and the DoD for joint DoD/NASA on-orbit maintenance and repair was signed in June 1986. The purpose of this MOA is to establish the collaborative relationship between NASA and the DoD to institutionalize on-orbit maintenance as a design option for current and future space systems. Under this MOA, NASA and the DoD have participated in the SAMS Study. A report on the initial stage of this study was released in June, 1987. Since this is an on-going study with no conclusions determined at this time, it will not be discussed in detail within this report.

Chapters 6 and 7 discuss insurance and pricing issues, respectively. Chapter 8 presents NASA goals and objectives and their relationship with possible national goals and objectives.

As an established highly defined procedure, satellite servicing can enhance, protect, and maintain satellites on orbit. While the universal application of this technology to all classes of free flyers and Space Station payloads is questionable, there exists a range of applications (see Fig. 1) which are entirely dependent on such servicing for their existence and for which on-orbit servicing at some level is appropriate. Satellite servicing is a valuable adjunct to our technology base, ensuring our ability to enhance and protect our capital investment in space satellites and vehicles while preparing a capabilities path to achievement of NASA and national goals in space.

Chapter 1: Experience To Date

o Experience to date with on-orbit satellite servicing, including cost of such operations and the fees charged to non-NASA users.

This segment of the report addresses major milestones in the development of satellite servicing within NASA over the past two decades. Impacts to cost are discussed throughout the report. Pricing policy and fees charged to non-NASA users are addressed in Chapter 7.

As a matter of record, component capabilities which make up satellite servicing have been under development since the Gemini days of the manned space program. The dramatic quality of EVA activity that took place during the Gemini program captured public attention although the activity was not performed with satellite servicing in mind; rather, it was aimed at exploring the capabilities of man in space. This capability exploration continued into the Apollo program and developed into an integral part of the Skylab program where unplanned EVA servicing activities were necessary to rescue the mission. To date, Skylab, Spacelab, and Shuttle middeck experiments have required some degree of Intravehicular Activity (IVA) servicing. The opportunity to demonstrate man's in-space capabilities was greatly expanded within the Shuttle program. In particular, EVA mobility was increased, satellites were retrieved and repaired in low-Earth orbit, and man's value to on-site problem-solving became clearer.

A major historical milestone summary of servicing capability development is presented in Fig. 2 and Fig. 3. Pre-Shuttle experience is summarized in Fig. 2, while Fig. 3 summarizes Shuttle-based experience. In addition to the milestones and accomplishments, their associated missions, and the mission dates, these figures also identify the types of servicing elements and capabilities demonstrated on each of these missions.

The following paragraphs provide a detailed description of the on-orbit servicing experience to the present time. Addressed are pre-1987 servicing

MAJOR HISTORICAL MILESTONES IN SERVICING CAPABILITY DEVELOPMENT
(PRE-SHUTTLE EXPERIENCE)

			SERVICING ELEMENTS & CAPABILITIES DEMONSTRATED						
MISSIONS	MILESTONES & ACCOMPLISHMENTS	MISSION DATES	EVA	IVA	RETRIEVING	REPAIRING	RESUPPLYING	UPGRADING	OTHER ELEMENTS & SUBELEMENTS*
GEMINI 4	•FIRST U.S. EVA	JUN 3-7, 1965	•						
GEMINI 6/7	•RENDEZVOUS & STATION KEEPING	DEC 15-16/4-18, 1965							•
GEMINI 8	•RENDEZVOUS & DOCKING	MAR 16-17, 1966							•
GEMINI 10	•EXPERIMENT HARDWARE RETRIEVED FROM DOCKED AGENA WITH EVA	JUL 18-21, 1966	•		•				•
GEMINI 12	•DOCKINGS & 3 EVA'S	NOV 11-15, 1966	•						•
APOLLO 7	•LIVE TV BROADCAST FROM SPACE	OCT 11-22, 1968							•
APOLLO 9	•CREW TRANSFER BETWEEN DOCKED SPACECRAFT	MAR 3-13, 1969	•	•					•
APOLLO 11	•EXTENSIVE EVA ACTIVITIES & SAMPLE RETURN	JUL 16-24, 1969	•	•					•
APOLLO 12	•RETURN OF ELEMENTS OF DEPLOYED SPACECRAFT (SURVEYOR 3)	NOV 14-24, 1969	•	•	•				•
APOLLO 13	•EXTENSIVE ON-BOARD PROBLEM SOLVING & RESOURCE MANAGEMENT	APR 11-17, 1970		•					•
APOLLO 15	•USE OF LUNAR ROVER & IMPROVED SPACE SUIT	JUL 26-AUG 7, 1971	•	•					•
APOLLO 17	•SATELLITE DEPLOYED IN LUNAR ORBIT	DEC 7-19, 1972	•	•					•
SKYLAB 2	•SUNSHIELD DEPLOYED & SOLAR ARRAY RELEASED DURING EVA •EXTENSIVE IVA	MAY 25-JUN 22, 1973	•	•		•			•
SKYLAB 3	•SUNSHIELD & RATE GYROS REPLACED WITH EVA • EXTENSIVE IVA	JUL 28-SEP 25, 1973	•	•		•			•
SKYLAB 4	•COOLANT SUPPLIES REPLENISHED •ANTENNA REPAIRED WITH EVA •SINGLE EVA DURATION RECORD	NOV 16, 1973 - FEB 8, 1974	•	•		•	•		•

* *Includes rendezvous, docking, elements of telerobotics, assembling, deploying, and returning*

Figure 2

MAJOR HISTORICAL MILESTONES IN SERVICING CAPABILITY DEVELOPMENT

(SHUTTLE-BASED EXPERIENCE)

			SERVICING ELEMENTS & CAPABILITIES DEMONSTRATED						
MISSIONS	MILESTONES & ACCOMPLISHMENTS	MISSION DATES	EVA	IVA	RETRIEVING	REPAIRING	RESUPPLYING	UPGRADING	OTHER ELEMENTS & SUBELEMENTS*
STS-7	•RMS DEPLOYMENT & RETRIEVAL OF SPAS-01 FREE FLYER	JUN 18-24, 1983			•				•
STS-9	•SPACELAB 1 WITH EXTENSIVE IVA	NOV 28-DEC 8, 1983		•					•
41-B	•MMU & FLUID PUMPING DEMONSTRATED • SMM REHEARSAL	FEB 3-11, 1984	•				•		•
41-C	•SMM RETRIEVED, REPAIRED & REDEPLOYED	APR 6-13, 1984	•		•	•			•
41-D/F	•31-M EXTENDED SOLAR ARRAY DEPLOYED & RETRIEVED •ICICLE REMOVED FROM SHUTTLE SURFACE WITH RMS	AUG 30-SEP 5, 1984							•
41-G	•ON-ORBIT FUEL TRANSFER & FUEL VALVE RETROFIT DEMONSTRATED	OCT 5-13, 1984	•				•	•	•
51-A	•PALAPA B2 & WESTAR VI RETRIEVED & RETURNED	NOV 8-16, 1984	•		•				•
51-B	•SPACELAB 3 WITH EXTENSIVE IVA	APR 29 - MAY 6, 1985		•		•			
51-F	•SPACELAB 2 RMS DEPLOYMENT & RETRIEVAL OF PDP	JUL 29 - AUG 5, 1985			•	•			•
51-I	•SYNCOM IV-3 RETRIEVED, REPAIRED AND REDEPLOYED	AUG 24-SEP 1, 1985	•		•	•			•
61-B	•EASE/ACCESS ASSEMBLY & DISASSEMBLY WAS FIRST SPACE STATION ASSEMBLY REHEARSAL	NOV 26-DEC 3, 1985	•						•

* *Includes rendezvous, docking, elements of telerobotics, assembling, deploying, and returning*

Figure 3

activities cited in Fig. 1 encompassing enabling technologies and actual on-orbit servicing experience.

ENABLING TECHNOLOGIES

Gemini Milestones

The Gemini program produced many significant milestones for the development of satellite servicing capabilities. The first American EVA was performed on Gemini 4 (June 3-7, 1965) by Astronaut Ed White. Gemini 6/7 demonstrated the feasibility of on-orbit rendezvous and station keeping and Gemini 8 demonstrated rendezvous and docking with a target vehicle. Capabilities continued to advance as Gemini 10 demonstrated the ability to retrieve experiment hardware from outside a spacecraft.

On Gemini 12, man-in-space capability was demonstrated outside the spacecraft during record-setting EVAs. Furthermore, the value of ground-based man-in-space simulation was demonstrated by this mission, when excellent correlation was observed between flight and simulation measurements of such EVA-related factors as astronaut heart rate, metabolic energy expenditure and manipulation of tools.

Apollo Milestones

Satellite servicing capability continued to evolve throughout the Apollo Missions. An essential component for future telerobotic servicing operations, live television, was first used in space by Apollo 7 (October 11-22, 1968). A major IVA capability was demonstrated on Apollo 9, when the first internal crew transfer between docked spacecraft (the Lunar Module and the Command Service Module) was successfully accomplished. The EVA experience base was dramatically extended on Apollo 11, when the first significant deployments occurred (a flag and numerous scientific instruments were placed on the lunar surface), and an extensive retrieval of samples performed. The first retrieval and return to Earth of elements from a previously deployed spacecraft (Surveyor 3) was performed by the crew of Apollo 12.

The value of man for extensive on-board problem solving, mission modification, and resource management became clear on Apollo 13 (April 11-17, 1970) when a fuel cell oxygen tank exploded, crippling the vehicle. On this mission, crew members extensively modified operation of their spacecraft systems and rationed limited on-board resources to survive their life-threatening emergency.

Significant mobility aids (the Lunar Roving Vehicle and an improved space suit) were successfully introduced on Apollo 15. On the final lunar mission (Apollo 17), the first satellite deployment from a manned spacecraft occurred when a scientific subsatellite was released into lunar orbit.

Skylab Milestones

Human participation in the execution of onboard experiments was an essential ingredient in the success of Skylab Missions. Although this occurred mainly in an IVA mode, the retrieval of data from some instruments required EVA. Man's ability to implement work-arounds for anomolous situations were fundamental to the success of this series of missions and proved conclusively that major elements of satellite servicing were technically feasible.

Crippling damage from the launch of the Skylab was repaired by means of EVA on the Skylab 2 (May 25-June 22, 1973) mission when a makeshift replacement sunshield was deployed, and the available electrical power was doubled by freeing a solar array which had failed to deploy. Skylab 3 crew replaced the laboratory's rate gyros and the makeshift sunshield with a more effective version. During the Skylab 4 mission (a final visit to Skylab), the astronauts demonstrated the first fluid replenishment (laboratory coolant), performed a repair of an external antenna, and set a new record of about seven hours for a single EVA.

Space Shuttle Achievements

The Space Shuttle has significantly expanded the potential for on-orbit service as a result of its unique capabilities, relatively frequent flight opportunities, and flexiblity. Satellite servicing capabilities, which were developed as an integral part of the manned program, have been applied directly to the on-orbit servicing of several unmanned satellites, with successful results. In addition, new capabilities, e.g., the use of the remote manipulator arm, have been developed, tested, and applied to on-orbit servicing tasks.

Servicing-related capabilities began development early in the Space Shuttle test flights with the first Remote Manipulator System (RMS) operations on STS-2 (Nov. 12-14, 1981). This capability was positively affirmed on STS-3 (March 22-30, 1982), when, for the first time, a payload (the Plasma Diagnostics Package) was removed and returned using the RMS. This package was lifted into space where measurement was achieved and then was swung back into its mount in the cargo bay. The crew of STS-7 provided a demonstration of proximity operations with the RMS deployment and retrieval of the SPAS-01 (Shuttle Pallet Satellite) free flyer. STS-9 carried out the first of four Spacelabs. All four Spacelab missions provided extensive IVA experience and demonstrated man's unique capability to maintain, repair, and if necessary, restructure experiments and equipment while on-orbit to obtain scientific benefits.

As a major milestone to the enhancement of EVA capabilities, STS Flight 41-B provided the first on-orbit demonstration of the Manned Maneuvering Unit (MMU), a device which greatly increases an astronaut's EVA range and mobility. Also on 41-B, fluid pumping was demonstrated and a contingency retrieval of an unintentionally deployed foot restraint occurred. The astronauts also practiced MMU docking for the upcoming Solar Maximum Mission (SMM) repair flight.

On STS 41-C, the Solar Maximum (SMM) Repair Mission (April 4-13, 1984), NASA planned and conducted its first formal experiment in on-orbit satellite servicing and repair. After an unsuccessful MMU (Manned Maneuvering Unit) docking attempt, the SMM spacecraft was grappled with the RMS, and maneuvered into the Shuttle's cargo bay. There the astronauts replaced the spacecraft's failed attitude control module and performed minor experiment repairs on the X-ray polychromator and the coronograph/

polarimeter science instruments with a single EVA. The Solar Max was then redeployed. The activity extended the operational life of the SMM and permitted significant gamma ray measurements to be made on the new supernova 1987a, as well as continuing SMM's long-term studies of solar activity. At this time, SMM continues to function as a scientifically productive spacecraft.

During the flight of STS 41-D/F, the RMS was deployed to remove a dangerous waste-water icicle from the Shuttle's exterior surface. An extended structure (a 31-meter solar array) was also deployed and retrieved. Mission 41-G demonstrated capability for on-orbit fuel transfer, and a fuel valve retrofit.

Probably the most highly visible satellite servicing events to date occurred on Mission 51-A; the retrieval and return to Earth of the Palapa B-2 (Indonesia) and Westar VI (Western Union) commercial communications satellites. Both satellites had been deployed from the Shuttle nine months earlier on Mission 41-B, but failures of their Payload Assist Modules (PAMs) resulted in their being placed in unusable low Earth orbits. The Palapa was retrieved first, followed by Westar. For both, the MMU was used for the initial capture; attachment hardware incompatibilities then forced the use of a manual contingency berthing procedure. Ultimately, both spacecraft were successfully returned to Earth, demonstrating NASA's capability to recover spacecraft from low Earth orbit.

An attempt was made on 51-D to repair the SYNCOM IV-3 satellite deployed on that flight by engaging a sequencer lever with a "fly-swatter" mounted to the RMS by means of EVA. (Analyses indicated that a switch lever on the satellite that activates the sequencer for the satellite may not have worked properly.) Although this particular attempt did not remedy the problem, the satellite was subsequently successfully retrieved and repaired during 51-I with an EVA. This mission clearly demonstrated that certain types of satellite repairs could be accomplished on-orbit.

Servicing experience with significance to Space Station assembly was demonstrated on Mission 61-B (November 26-December 3, 1985) during the

EASE/ACCESS structure operations. Two sample designs for Station truss structures were repeatedly erected, manipulated, and disassembled to gather timeline and engineering data. Installation of simulated utility lines was also performed, and the ability to repair components in an assembled truss structure was demonstrated.

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o The use of the Shuttle, the Station, and other space vehicles to carry out or support satellite servicing.

OVERVIEW OF SERVICING-BASE CONSIDERATIONS

The existing STS and the planned Phase 1 Space Station are two manned facilities from which activities may be conducted to support on-orbit servicing. All servicing currently requires the direct support of humans in space and is Shuttle-based. Because of the propulsive energy required to change the orbital inclination of earth orbiting vehicles, and Shuttle operational capability, only free flying satellites in orbits with inclinations in ranges 28 degrees to 57 degrees and altitudes up to about 320 nautical miles can be serviced. This range can be extended up to 1400 nautical miles with plane changes of up to 7.5 degrees with the planned Orbital Maneuvering Vehicle (OMV).

Should the Vandenberg STS launch capability eventually be activated, high inclination (polar) satellite orbits could also be accessed from an STS base. Otherwise, high inclination satellites will have to rely on remote, robotic, or telerobotic, Expendable Launch Vehicle (ELV) based servicing capability that has yet to be developed. Such a capability is already being studied by NASA in its Earth Observing System (EOS) Phase B studies, and was assumed to be a primary servicing tool in the NASA/DoD SAMS study.

Orbital regions defined in the SAMS study are: low altitude/low inclination, low altitude/mid inclination, low altitude/polar orbit, high altitude/mid-inclination, and geosynchronous. The potential means of access to each of these five orbital regions is indicated in Fig. 4. Shaded areas in a row of this table represent regions which are inaccessible by the corresponding vehicle. Note that some vehicles exist, some are in the planning stages, and some are at a purely conceptual stage. A coarse timeline (see Fig. 5) illustrates how these vehicles may be used. This figure is intended to serve only as an example.

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VEHICLE APPLICABILITY TO ORBITAL REGIONS

ORBITING REGION / VEHICLE	LOW ALTITUDE/ LOW INCLINATION	LOW ALTITUDE/ MID INCLINATION	LOW ALTITUDE/ POLAR ORBIT	HIGH ALTITUDE/ MID INCLINATION	GEO-SYNCHRONOUS
STS	●	●	ASSUMES VAFB LAUNCH	▨	▨
SS	●	▨	▨	▨	▨
OMV	FROM THE STS OR SS	FROM THE STS OR SS	FROM THE STS ONLY	FROM ELV	▨
OTV	▨	▨	▨	FROM THE STS OR SS	FROM THE STS OR SS
ELV	●	●	●	●	●
COMMENTS	(1) SERVICING OF FREE FLYERS / PLATFORMS AT THE SS INVOLVES RETRIEVAL BY OMV / OTV (2) POLAR ORBITING SPACECRAFT CAN BE SERVICED FROM STS (VAFB LAUNCH) OR ELV's ONLY				

Figure 4

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USE OF STS, SS AND OTHER VEHICLES FOR SERVICING*

	STS	*SS*	*OTHERS*
NEAR TERM CURRENT - 1994	● FREE-FLYER SERVICING	● N/A	● N/A
MID TERM 1994 - 2000	● FREE-FLYER SERVICING ● SS ASSEMBLY ● RESUPPLY OF SS	● SERVICING OF SS ATTACHED PAYLOADS ● SERVICING OF FREE FLYERS & PLATFORMS	● USE OF OMV TO DEPLOY AND RETREIVE FREE FLYERS
LONG TERM > 2000	● FREE-FLYER SERVICING ● RESUPPLY OF SS	● SERVICING OF SS ATTACHED PAYLOADS ● SERVICING OF FREE FLYERS & PLATFORMS ● ASSEMBLY OF LARGE PAYLOADS	● USE OF OMV/OTV TELEROBOTIC SERVICING ● USE OF OTV TO TRANSFER TO AND FROM GEOSYNCHRONOUS ● USE OF ELV'S

Figure 5

**Note*: *Many of the mid and long term payloads are still in the planning and development stage and have not yet been approved for development*

As a result of the previous on-orbit servicing activities discussed in Chapter 1, NASA has already developed an extensive array of ground support equipment, flight support equipment, and Shuttle-based servicing hardware and capabilities. Additional ground-based and space-based elements are currently being developed to support planned NASA on-orbit servicing activities, such as the maintenance and upgrade of the Hubble Space Telescope, and the on-orbit refueling of the Gamma Ray Observatory. A comprehensive servicing facility, including a protective enclosure, external storage facilities, work benches, and a dedicated remote manipulator system, has also been defined as part of the Space Station Phase B study activities. This facility will not be implemented as part of the Phase 1 Station but may be incrementally developed, as part of a continued Station evolution, as required to support user demands.

The following sections provide an overview of the existing and planned servicing capability including servicing support facilities, equipment, tools and aids developed by NASA for use in its continuing on-orbit servicing activities.

Shuttle

In the near term, i.e., until the mid to late 1990's, the Shuttle will be the only manned facility available to support on-orbit servicing. Although more limited than the Space Station, in terms of the servicing materials that can be aggregated on-orbit to support a specific servicing mission and the amount of EVA and IVA time available, the Shuttle has three advantages:

a) Flexibility of access to low to mid-altitude, mid-latitude, orbiting satellites;

b) Ability to rendezvous with a satellite; and

c) A crew.

OMV/OTV

A key capability expansion of Shuttle-based and Station-based servicing is the Orbital Maneuvering Vehicle (OMV) which can be used for satellite placement, retrieval, and reboost. The OMV is now in development with a planned initial capability of 1993. It is a reusable, remotely controlled, free-flying system capable of performing a wide range of on-orbit services in support of orbital payloads.

Multiple propulsion systems and on-board avionics will enable the OMV to deliver and retrieve satellites in orbits not otherwise achievable from the Shuttle. Precision maneuvering for proximity operations (including docking with an orbiting satellite) will be accomplished by man-in-the-loop control via an OMV control station. Eventually, both the OMV and the OTV might also be equipped with "smart front ends" (i.e., with robotic or telerobotic servicers) so that in-situ satellite servicing could also be conducted. When used with the Shuttle, the OMV will be carried into orbit as part of the servicing payload. For Station-based servicing, the OMV will be stored at the Station and will be used for multiple servicing events before being returned to earth. Thus, the OMV can be both a servicing tool and a servicing candidate in the Space Station era.

The OTV is planned as an advanced upper stage that will carry cargo, and perhaps humans, from low Earth orbit to geosynchronous orbit and beyond. The exact capabilities and configuration of the OTV will be defined in the early 1990's in parallel with NASA's new initiative definitions. In past studies of OTV concepts, several options have been the subject of trade-off studies. These include: the use of cryogenic or storable propellants; a reuseable or expendable design; ground-basing or space-basing; an all-propulsive vehicle or the use of an aerobrake for return flights; and delivery to low Earth orbit on the Shuttle or on a cargo vehicle. In most concepts, the OTV has the flexibility to evolve to meet increased mission requirements. For example, the initial OTV may be designed to deliver payloads to geosynchronous orbit, while a later version may be used to ferry humans between low Earth orbit and the Lunar surface. The initial OTV will most likely be a cryogenic vehicle with the capability to deliver at least 10,000 pounds of cargo to geosynchronous orbit or propel equivalent payloads to the Earth escape velocities required for advanced planetary exploration.

Space Station

The baseline Space Station (Phase 1) will have the capability to service and upgrade its own facilities as well as the internal and external attached payloads. There will also be a capability to provide, on a case-by-case basis, some servicing of free-flyers in the vicinity of the Station. Servicing elements will include the FTS, the Phase 1 Mobile Servicing Center (MSC) which includes the RMS, a mobile transporter, and standard equipment such as servicing tools and translation aids. These elements, in combination with the permanent presence of astronauts in an environment more controlled than that of the Space Shuttle, ensure a far more extensive EVA servicing capability than previously available.

Studies will be conducted to maintain the option of providing an effective early servicing capability for free-flyers and attached payloads. These studies will reveal more precisely how to take advantage of the capabilities afforded by the baseline Station. A first step is evaluating the capabilities needed to satisfy servicing, assembly and storage requirements. Additional efforts will analyze possible EVA servicing aids that might include a case-by-case application of sun-impingement protection, thermal control, and contamination traps, shields, and tents. The IVA servicing capability, including the workbench area, is available to support EVA.

Program plans include servicing the ESA-provided Man-Tended Free-Flyer (MTFF) at the Space Station after the completion of assembly and operational verification. Additional free-flyers that may be serviced from the Space Station include commercial platforms, the Hubble Space Telescope and the Gamma Ray Observatory, AXAF, SIRTF, as well as other OSSA assets that require servicing. As the Station evolves, one possibility is to add a more extensive servicing capability as the initial increment of Space Station evolution. These capabilities could include an enclosed full-sized servicing facility and Orbital Maneuvering Vehicle (OMV), enhancements to the MSC, and an additional RMS.

ELV

The use of Expendable Launch Vehicles (ELVs) for on-orbit servicing of satellites is still in a preliminary stage of study, and requires the development of expanded vehicle capabilities, such as automated docking and servicing capabilities. ELV-based servicing has the potential advantage of access to spacecraft at all orbital inclinations and altitudes and the disadvantage that the servicing payload cannot be returned to earth after the servicing event. Possible solutions to this dilemma, currently under study by NASA and the DoD, include off-loading the robotic servicing devices from the ELV onto the spacecraft or platform and using them to support "self servicing" throughout the operational life of the spacecraft. No NASA mission has yet baselined the use of such on-orbit servicing, although the EOS mission is still considering this approach in its tradeoff studies, together with the use of non-serviceable (expendable) spacecraft.

Spacecraft Rendezvous and Retrieval

Retrieval of spacecraft for servicing requires that the orbital planes of the spacecraft and the servicing vehicle are in alignment. The opportunities for co-alignment range from a daily launch window for a KSC launched, dedicated STS servicing mission, to opportunities permitted by alignment of a spacecraft to be serviced by Space Station. These servicing opportunities may range from days to periods greater than one year. This happens due to the differential precession of the orbits. STS-shared retrieval missions may have constrained launch windows, and therefore may have fewer than daily launch opportunities because of manned spaceflight constraints such as lighting conditions, the launch-window constraints of other payloads, or other factors.

For Space Station based servicing of the Hubble Space Telescope, which does not have its own propulsion capabilities, the Hubble Space Telescope orbit plane and the Space Station orbit plane will align approximately every 14 months and will remain aligned sufficiently to allow retrieval for several days. This interval is the "plane window." Frequency of orbit plane alignment depends on the respective altitudes of the two orbits. Actual accessibility for rendezvous and retrieval, the "phase window," will vary and is dependent on the operational capabilities of the Space Station, the OMV, and the spacecraft to be serviced.

Careful planning to assure successful rendezvous and retrieval of spacecraft for service is required. Given the above considerations of orbital mechanics, servicing missions launched from KSC may be appropriate where more frequent orbital alignments are required, while the Space Station may be utilized for preplanned repair and maintenance of spacecraft.

EXISTING SERVICING HARDWARE AND CAPABILITIES

This segment of the report discusses hardware and capabilities that are existing, under development, and planned. In order to undertake the various on-orbit servicing activities that have been required to support NASA's manned space program, an extensive array of ground-based and space-based support equipment, crew aides, tools, and procedures has been developed. This array of servicing hardware and capabilities has been further refined and extended to support NASA's planned Shuttle-based on-orbit servicing experiments. As a result, there currently exists versatile equipment and an associated experience base on which new users of NASA's on-orbit servicing capability can draw. NASA now has a catalogue of existing servicing tools which is in the process of being updated and plans soon to publish the new version.

The development of standard on-orbit servicing equipment and procedures is potentially of great value to NASA and non-NASA programs planning to make use of this new capability. First, the use of such equipment reduces the mission-unique development costs associated with on-orbit servicing. The use of standardized tools and procedures also reduces the servicing crew's ground-based training time, and lessens the risk of expensive mistakes on-orbit. In addition, since NASA has expended significant effort in making its equipment as efficient and reliable as possible, subsequent users can realize the benefits of this design optimization process. An example of such an optimized servicing tool is the Programmable Power Ratchet Tool, which may be regarded as the power driver analog of a conventional ratchet handle with unique control features. The concept originated at Marshall Space Flight Center in the course of man-in-space evaluations for Hubble Space Telescope (HST) servicing options. In searching for ways to speed up tedious manual operations, the advantages of a pneumatically powered ratchet driver were dramatically apparent. More significantly, such a tool may well make the difference in the completion of a mission. These types of tools and activities are expected to become standard through common use. Man-in-space activity that occurs while wearing a pressure suit is fatiguing and restricting; use of power tools offers reduction of these negative operational factors and improves and prolongs the productivity of the crewmember.

Existing Shuttle-Based Servicing Hardware and Capabilities

Flight-qualified Shuttle-based servicing hardware and capabilities (most of which have already contributed to successful servicing missions) are listed in Fig. 6 on the following page. The functional applicability of each servicing tool is described below:

EVA:

o Module Service Tool--powered device which drives the connection interface for equipment modules such as used on the Solar Maximum spacecraft.

o Smart Programmable Power Ratchet Tool--a recent development aimed at reducing the physical and mental workload in hardware interface operations.

o Monopropellant fluid coupling--developed as a working EVA operable model to stimulate incorporation of such interfaces in near-term spacecraft.

o Electrical connectors--self-aligning electrical connectors with internal circuit components are protected from damage during the engagement sequence.

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EXISTING SHUTTLE-BASED SATELLITE SERVICING HARDWARE AND CAPABILITIES

	RETRIEVING RESUPPLYING	REPAIRING	UPGRADING	DEPLOYING	ASSEMBLING CONSTRUCTING
FLIGHT QUALIFIED HARDWARE					
•EVA					
MODULE SERVICE TOOL	•	•	•	•	•
SMART POWER RATCHET TOOL	•	•	•	•	•
EVA FLUID COUPLINGS (MONOPROP.)	•				
ELECTRICAL CONNECTORS	•	•	•	•	•
FLIGHT SUPPORT SYSTEM (FSS)	•	•	•	•	•
HAND TOOLS	•	•	•	•	•
MMU	•		•		•
•RMS	•	•	•	•	•

Figure 6

- Flight Support System (FSS)--used for holding spacecraft of various designs in the Shuttle bay so that they can be serviced.

- Miscellaneous hand tools--EVA-adapted versions of common tools (ratchets, vise grips, etc.).

- MMU--multipurpose astronaut mobility unit allowing short-range free flights.

RMS:

- RMS--a 55-foot teleoperated arm baselined STS mechanism for spacecraft deployment and proximity manipulation.

Associated Ground-Support Equipment and Facilities

Significant ground-based support equipment and facilities, which are an essential part of satellite servicing activities, exist at the various NASA space flight centers. These resources include neutral-buoyancy tanks, Shuttle and Space Station models and simulators, large air-bearing floors, dynamic docking simulators, robotic simulators, and Shuttle payload integration facilities. These facilities are essential because they provide realistic crew training in servicing activities, and verification of servicing hardware and procedures. They also facilitate mission planning and support all aspects of hardware design and development. These facilities will be made available to potential non-NASA servicing users on a cost-reimbursable basis.

SERVICING DEVELOPMENT ACTIVITIES

In addition to the array of existing hardware and facilities identified above, there are a number of potentially powerful servicing support systems currently in development. The systems will apply generally and support specific programs, like the Hubble Space Telescope, the Gamma Ray Observatory, AXAF, SIRTF, and EOS.

This section presents summary schedules for servicing hardware development and flight experiments (Fig. 7).

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SATELLITE SERVICING HARDWARE DEVELOPMENT STATUS

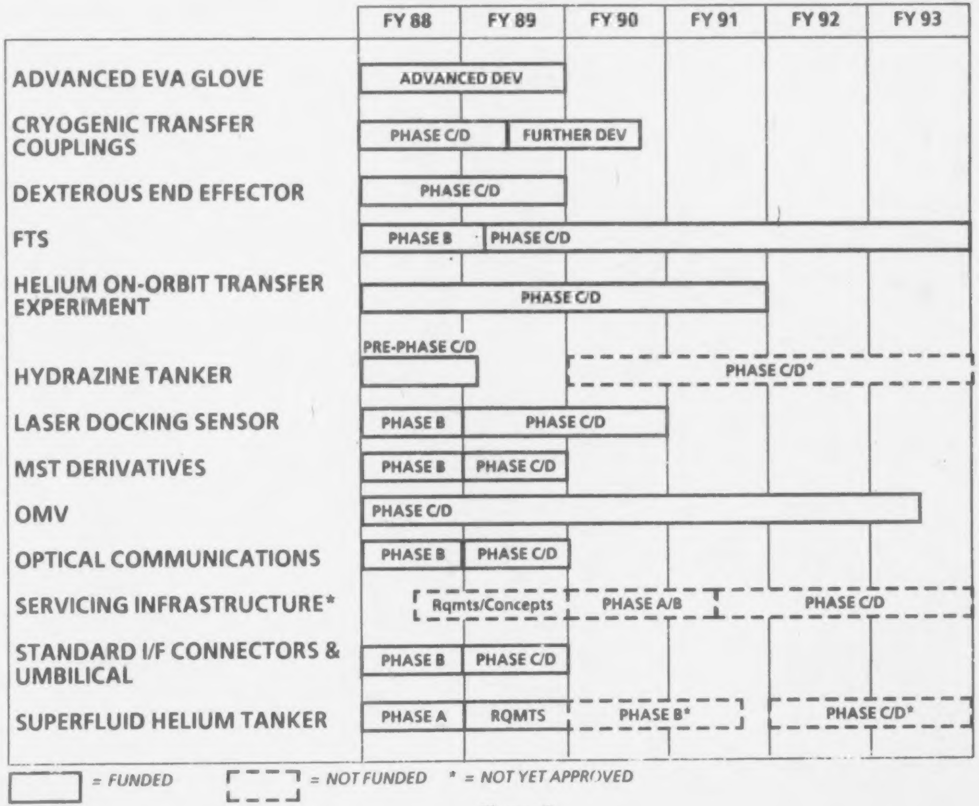

Figure 7

Following are descriptions of each major hardware item and experiment currently being developed:

o Advanced EVA Glove--a funded project designed to increase dexterity, tactile sensing and mobility, and to decrease effort in hand work during EVA.

o Cryogenic Transfer Couplings--a funded project being developed as an EVA model for incorporation in near-term spacecraft.

o Dexterous End Effector--a funded project combining force/ torque sensor with a mechanical hand for the RMS to allow more refined RMS operations than currently achievable.

o Flight Telerobotic Servicer (FTS)--a robotic system designed to assist in Space Station assembly and maintenance, and to be structured for evolutionary capabilities.

o Helium On-orbit Transfer Experiment (SHOOT)--a funded project for development of a Shuttle-based, in-bay demonstration of superfluid helium transfer under operational conditions will be performed.

o Hydrazine Tanker--being designed for spacecraft refueling. Prephase C/D has been funded; Phase C/D is not yet approved nor funded.

o Laser Docking Sensor--a funded project for the development of hardware designed to track a passive orbital target spacecraft with sufficient accuracy to enable soft docking with minimal thrusting near the target vehicle.

o Module Service Tool (MST) Derivatives--a funded project for development of end effectors modified to be mounted on the end of the RMS to facilitate non-EVA servicing operations from the STS; Lightweight MST--modified to reduce weight and facilitate ease of operation, and to operate as a front-end tool on the Flight Telerobotic Servicer (FTS), OMV and other teleoperated or remote servicing facilities.

o Orbital Maneuvering Vehicle (OMV) --a funded project to develop a reusable propulsion stage capable of transporting spacecraft and other payloads between low Earth orbit trajectories.

o Optical Communications--a funded project to provide local high bandwidth point-to-point communication capability for operations from the STS aft flight deck to local servicing sites.

o Servicing Infrastructure--coordinated hardware and technology development to support a well-defined user requirement database. Project is not yet approved for funding.

o Standard I/F Connectors and Umbilical--a funded project for development of a remote mateable/ demateable flexible umbilical connector to provide a remotely operated umbilical connector capability for electrical, gas, and fluid services; and the Umbilical Carrier Mechanism (with the passive half of the umbilical and carrier on a satellite to be serviced and the active half on the Shuttle) controls the connection of umbilicals to minimize disturbances to the satellite and Shuttle.

o Superfluid Helium Tanker--designed to resupply cryogenic coolants on board the SIRTF and possibly, the second-generation Hubble Space Telescope and AXAF instruments. Phase B and Phase C/D are not yet approved nor funded.

SERVICING EVOLUTION CONSIDERATIONS

As noted earlier in this report, on-orbit servicing is a capability which is still in an early stage of evolution. From the servicer side, it depends on the successful evolution of the current Shuttle-based capability and facilities of the Space Station. Once servicing support and facilities are available at the Station, further development of telerobotic and robotic servicing capabilities will take place. Such capabilities will benefit all servicing users, since they will decrease dependence on EVA. They will also benefit potential servicing candidates operating in orbits inaccessible to the Shuttle and Space Station.

With the advent of the OMV, many forms of spacecraft services will become possible. The OMV or the OTV may be used to return spacecraft to the STS or the Space Station for maintenance and/or resupply. In addition, direct spacecraft servicing may be performed by adapting special purpose mission kits to the OMV or the OTV which are capable of performing remote or in-situ maintenance of spacecraft, thus eliminating the need to return payloads. Fuel efficiency of telerobotic or robotic OTV servicing missions to spacecraft in geostationary orbits could be further enhanced by the use of aerobraking to assist in the return from geostationary orbit.

The remote services may take two generalized forms; remote module exchange of failed spacecraft elements or replenishment of onboard expendables. Perhaps both may be desirable on the same mission. These functions, in effect, extend man's ability to perform maintenance and other mission support operations remote from the STS through the adaptation of specialized "effectors" or servicing and refueling kits.

In addition to the previously mentioned functions, it has long been recognized that a need exists to be able to capture unstable and/or inactive spacecraft and certain classes of debris. Ongoing studies are being directed toward the definition and development of systems to expand the OMV capability for capture. This interest addresses the economic value of some classes of spacecraft which have failed prior to the end of their useful life and threaten collision with other orbiting systems. Such spacecraft could be recovered and reflown as was demonstrated in the retrieval, repair and redeployment of the Solar Maximum Mission spacecraft.

Where costs of on-orbit servicing are associated with NASA's servicing support, the agency will continue its efforts to develop more efficient and reliable support equipment and facilities. NASA will also provide potential users with guidance on how best to make use of on-orbit servicing. This advice will be drawn from the NASA user's own experience in using on-orbit servicing to assemble structures, to maintain or repair systems, to resupply consumables, to upgrade payloads, and to retrieve, deploy or return spacecraft and payloads.

Since the integrated logistics support required for few-of-a kind missions will continue to be a significant cost driver, NASA will continue to develop and promote the use of common systems and subsystems, as well as common interfaces, support equipment, and tools. This will reduce the cost of on-orbit servicing.

NASA is performing studies to determine the feasibility of employing ELV-based robotic servicing in polar orbits. The two concepts under study utilize a service carrier which is launched on an ELV. After rendezvous and docking, one scenario features a resident robot that exchanges ORUs and payloads which use Standard Interface Connectors (SIC). The service carrier is discarded. In the second scenario, the service carrier remains attached and functions as an extension of the original platform. NASA is considering generating guidelines to payload designers so that they may incorporate generic design features to facilitate possible future robotic servicing.

Finally, NASA will continue to look at the requirements and benefits of on-orbit servicing capabilities on a program by program basis, and will balance the life-cycle costs of such an approach with the scientific, commercial, or programmatic needs and benefits.

Chapter 3: Servicing Design Considerations

o Pertinence of satellite servicing to satellite and vehicle design.

Two kinds of programs currently plan to use on-orbit servicing. The first, which includes the Space Station and life science and materials processing programs, requires on-orbit servicing as an enabling activity; they cannot exist without it. The second, which includes the Great Observatories (Hubble Space Telescope, GRO, AXAF, and SIRTF), the planned reuseable Explorers, and the Earth Observing System (EOS) platforms, will use on-orbit servicing as an enhancing capability to achieve extended operational lifetimes and/or mission flexibility. These missions could, in theory, achieve their program goals by other means, but choose to use the servicing infrastructure to benefit their missions.

For both kinds of programs, planning for on-orbit servicing has to begin at a very early stage in the program definition process; i.e., in the feasibility and conceptual study activities. Some of the most fundamental decisions that must be made concern the tradeoffs between scientific (or program) goals and objectives and the need for manned or unmanned on-orbit servicing. Thus, a solar physics or astrophysics mission may have to balance the scientific benefits of the continuous observations possible at geosynchronous orbit against the extended operational lifetime and scientific payload upgrade potential of a more accessible spacecraft.

ON-ORBIT SERVICING CONSIDERATIONS

Once on-orbit servicing has been established as desirable for a program, then studies must be undertaken to determine such factors as: systems architecture; level of modularity of spacecraft and payload; degree of reliability; frequency of servicing needed during lifetime of spacecraft; and level of commonality of systems or subsystems internal and external to the Mission. Inherent in the design decisions associated with serviceability are those which make the planned on-orbit servicing activities safe and efficient for human servicers and feasible for the less dexterous robots. For example, a means must be provided to make the spacecraft safely approachable. If the spacecraft is to be transported to another location before servicing commences, its structure must be capable of surviving the loads (i.e., shock, acceleration, vibration, etc.) imposed by the transporter. The spacecraft also must be protected from contamination sources during all phases of the servicing process, and the thermal environment maintained in a safe range throughout the operation.

Another important consideration in the design process is the allocation of interface responsibilities. For example, in the case of satellite capture and retrieval, the first concern in approaching a satellite is to eliminate both straight-line motion and rotation. For broadest applicability, this responsibility should be given to the servicer, since some spacecraft may be rendered inactive by the failure which prompted the servicing mission. The next concern is whether the spacecraft geometry allows a servicer to get close enough for docking; a rearrangement of appendage placement may be necessary. Obviously, servicer attach points must be made available at the docking area, and EVA handholds must be provided for manned servicing targets. Protective covers must be installed for fragile satellite structures, and satellite hazards to the servicer or astronaut must be eliminated.

If the servicing operation is not to take place in-situ but rather at a distant base, the satellite must be able to survive the transportation environment. Provision must be made for appendage stowage and subsequent redeployment if launch loads exceed survivable limits. If the satellite's thermal conditioning and power systems are adversely impacted during the transportation phase, the servicer must be capable of supplying the appropriate supplements to the satellite if required.

Spacecraft Modularity

If design solutions to all of these concerns can be found, the question of robotic versus human servicers and human servicer skill level must then be addressed. It is generally accepted that the easiest and most efficient on-orbit servicing requires modularization of a spacecraft into a number of easily exchanged Orbital Replacement Units (ORUs). The fewer the ORUs, the easier the on-orbit servicing event. However, ease of on-orbit servicing must be balanced against the potential cost of replacing an ORU containing both failed and functional systems. Transportation to and from space to support the servicing event must also be taken into consideration. Ideally, today's satellite ORUs should be designed for manipulation in both EVA and remote servicer modes; this includes considerations for grappling points, mass, and geometry. The ORUs should be designed for easy insertion and removal in both modes. The considerations here are for alignment aids, interface verification, and connection designs for power, thermal, fluid, and communication services between the ORU and satellite core.

Spacecraft Environmental Considerations

Another ORU design concern is that of survivability during the space transportation, on orbit storage, and exchange processes; for example, some satellites will have varying degrees of sensitivity to contaminants emanating from the Shuttle and from the servicer. They will also be sensitive to the thermal environment (ORUs will also be sensitive to this environment). Although the ORU carrier will afford some level of contamination control and thermal protection and the servicer system will be designed to be as clean as possible, this concern still needs to be addressed by all satellites. Solutions to these concerns may involve servicer-installed covers for sensitive satellite components or servicer-provided thermal screens or enclosures.

DESIGN CONSIDERATIONS FOR ON-ORBIT SERVICING

The modular design of spacecraft required to facilitate on-orbit servicing has both positive and negative impacts. On the positive side, modularity and accessibility can make satellite integration and test more efficient.* A study for NASA by Martin Marietta estimated a 4% incremental cost increase for design and development and an estimated 8% per unit recurring cost increase for hardware.* A serviceable design may also result in a heavier spacecraft, with a 5 to 10% weight increase being estimated by many builders.

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*"The NASA/GSFC MMS Experience", Edward Falkenhayn, December 1987.

Other factors which must be considered by the users of payloads on serviceable spacecraft include: reduced surface space due to the presence of grapple fixtures and handholds; increased opportunity for damage during the servicing event; and probable down-time for spacecraft systems and payloads during servicing. Some positive considerations are the opportunities for expendables replenishment and instrument upgrades, repairs, or replacements.

Reliability

A vital question that must be addressed by the spacecraft designers is that of system reliability and the frequency of the servicing event. Clearly, there is great benefit to be gained from making spacecraft systems as reliable as possible to reduce servicing costs. Even when servicing is planned to effect the exchange or upgrade of a payload, or to replenish consumables, it is still desirable to reduce other servicing activities and the associated costs of servicing support. Ultimately, a limit is reached in which the cost of obtaining, screening and selecting high reliability parts and the associated weight penalties makes further reliability expensive compared with the cost of on-orbit servicing. The user must recognize this point and establish his reliability requirements prior to the start of the design phase.

Integrated Logistics Support Requirements

In designing a spacecraft for on-orbit servicing, and making the tradeoffs implied above, the more mundane requirements of ground-based and space-based logistics must not be forgotten. These requirements include: spares, tools, repair and refurbishment facilities, ground support equipment, ground test equipment, shipping and handling equipment, documentation, sustaining engineering, crew training, flight support equipment, ground transportation, space transportation, and special crew aids and tools. While space transportation and the design for on-orbit servicing are both significant cost drivers in a user's budget for on-orbit servicing, the integrated cost of the remaining items can also be significant unless care is taken at the beginning of the program to minimize these costs.

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*Report MCR-86-1339, Martin Marietta, Contract NAS 835625 with MSFC.

The most effective way of reducing these residual costs is by use of standardized systems and subsystems. This allows several programs to share the cost of most of the ground-based and space-based support elements listed previously. The use by the Solar Maximum Mission of the Multimission Modular Spacecraft (MMS) assured the availability of spare spacecraft modules (ORUs) even though no provisions had been made for such a repair attempt within the program. The planned use of the Explorer Platform will exploit this capability for future Astrophysics Explorer Missions. Recognizing the significant benefits of commonality at both the system and subsystem level, the Space Station program has dictated that commonality be maximized throughout the Station and its Platforms.

Chapter 4: Satellite Servicing Implications

o Pertinence of satellite servicing to NASA and other space programs, including science and applications programs.

The Solar Maximum Mission Repair was a highly visible and successful demonstration of NASA's ability to rapidly (i.e., within one year) mount and implement an unplanned repair mission on a modular spacecraft. The repaired SMM spacecraft has continued to collect valuable observations of solar activity during the ascending phase of this solar cycle and has obtained dramatic new gamma ray measurements on the supernova 1987a.

A major advantage of on-orbit servicing is that it has made possible the concept of the Great Observatories Program. By extending the on-orbit lifetime of four major astrophysics observatories: the Hubble Space Telescope (HST), the Gamma Ray Observatory (GRO), the Advanced X-Ray Astrophysics Facility (AXAF), and the Space Infra-Red Telescope Facility (SIRTF), it should be possible to achieve periods of overlap (or near overlap) between different sets of the Great Observatories, such that contemporaneous measurements can be made. The capability to make contemporaneous multispectral observations of selected features and phenomena in the universe will enable the world's astronomers to rapidly make significant advances in all fields of astrophysics.

The Great Observatories Program development is already underway. Both GRO and HST have already been approved and are in advanced stages of development. AXAF is a candidate for an FY 1989 new start, and SIRTF is in an advanced design stage, aiming at a new start in the early 1990s.

The first (visible and ultraviolet) element of the Great Observatories Program, the Hubble Space Telescope, was the first NASA payload specifically designed to make use of on-orbit servicing. The initial rationale for on-orbit servicing of HST was to assure long-term scientific excellence for the mission, through progressive introduction of ever-more capable scientific instruments at the focal plane of the 2.4-meter aperture telescope. The HST will function in space in exactly the same way that a major ground-based observatory functions on the ground, with provision made both for general observers and for a limited number of new instrument builders.

The second (gamma ray) element of the Great Observatories Program, the Gamma Ray Observatory, was not initially designed for on-orbit servicing. However, GRO's use of the MMS renders the spacecraft serviceable on-orbit. NASA now plans to replace MMS modules and replenish the GRO propellants as required to achieve an extended mission life. The nature of GRO's massive, complex, and intricately designed science instruments makes them impossible to replace on-orbit. However, most of the GRO instruments have inherently long design lifetimes and extensive scientific potential, and are hence compatible with the Great Observatories concept.

Although the remaining two elements of the Great Observatories Program have not yet received approval to enter the development phase, both are being designed to make use of on-orbit spacecraft servicing to achieve extended mission lifetimes. The third (x-ray) element of the program, AXAF, is a large aperture (1 meter) grazing incidence multi-element telescope with a cluster of scientist-developed instruments in its focal plane. Like the HST, AXAF will assure long-term scientific excellence through replacement of selected elements of the payload at later phases of the program. AXAF is also likely to make use of modular spacecraft systems which are common to those of the GRO or the HST. Thus the AXAF servicing program will also enjoy some of the benefits of system commonality.

The fourth (infra-red) element of the Program, the Space Infra-Red Telescope Facility (SIRTF), is also a large aperture telescope with a cluster of scientist-developed instruments at its focal plane. However, in order to make measurements in this wavelength range, both the telescope and the instruments must be cryogenically cooled. The availability of on-orbit servicing will enable SIRTF's cryogens to be replaced when necessary, as well as allowing failed or degraded spacecraft systems to be replaced. However, because of the design of the cooling system, scientific instrument replacement may not be possible. The SIRTF may achieve system commonality through use of HST or GRO-type spacecraft modules or may be the first Space Station co-orbiting platform.

Other Divisions within OSSA have similar plans. In particular, the Earth Sciences and Applications Program plans to make use of the Space Station's polar orbiting platforms as part of its Earth Observing System (EOS) program. EOS is currently in the planning phase, aiming for a new start in the early 1990s. On-orbit servicing from a Vandenberg-launched Shuttle or from an ELV would provide extended operational lifetimes and operational flexibility, and are options being evaluated. Additionally, both the Space Physics Division and the Solar System Exploration Division plan to use on-orbit servicing to assemble and maintain a number of Space-Station-associated attached payloads and near-orbiting spacecraft.

Of particular importance in the Space Station era are OSSA's plans for microgravity life sciences and materials sciences research. Facilities are being designed by NASA and the private sector to support both branches of microgravity research. The plans for NASA facilities are also being coordinated with those of the Station's international partners, the European Space Agency (ESA), Japan, and Canada, since all three plan similar facilities. On-orbit servicing in the form of resupply of consumables, harvesting of samples, and repair of failed systems is an inherent, enabling activity for both of these programs. Without such on-orbit support, research cannot be undertaken which will lead to commercial exploitation of the microgravity manufacturing environment, and commercial man-tended space processing ventures. It should be noted that these ventures will have to make use of both on-orbit servicing of the commercial (materials processing) payloads, and of the parent spacecraft or platforms. Thus, commercial users will benefit from NASA's on-orbit servicing of free flyers as well as support of the materials processing activities.

A summary of NASA's satellite servicing requirements is provided in Fig. 8a and Fig. 8b. These requirements exhibit varying degrees of firmness in terms of eventual implementation, the firmest of which are those derived from the published NASA FY88 budget, including out-years. Longer range

OSSA CANDIDATE MISSIONS FOR SHUTTLE-BASED SERVICING

MISSION	STATUS OF SPACECRAFT/ LAUNCH/ SERVICING	POTENTIAL SERVICING REQUIREMENTS				PROJECTED TIME FRAME
		RETRIEVING	REPAIRING	RESUPPLY-ING	UPGRADING	
SPACELAB MISSIONS	ANNUALLY BEGIN'G IN 89 PLANNED	●	●	●		89 - 96
SOLAR MAX RETRIEVAL	ON ORBIT	●				90
HUBBLE SPACE TELESCOPE	IN ASSEMBLY 6/89 PLANNED	●	●		●	92
EXPLORER PLATFORM	IN ASSEMBLY 8/91	●	●		●	MID
GAMMA RAY OBSERVATORY	IN ASSEMBLY 1/90 PLANNED	●	●	●		94
ADV X-RAY ASTROPHYSICS FACILITY	95 PLANNED	●	●	●	●	98
SPACE IR TELESCOPE FACILITY	96 PLANNED	●	●	●	●	98
EARTH OBSERVING SYSTEM (EOS)	95 PLANNED	●	●	●	●	98

Figure 8a

OTHER SHUTTLE - AND STATION-BASED SERVICING MISSIONS

MISSION	STATUS OF SPACECRAFT/ LAUNCH/ SERVICING	SERVICING REQUIREMENTS				PROJECTED TIME FRAME
		RETRIEVING	REPAIRING	RESUPPLY-ING	UPGRADING	
LDEF RETRIEVAL	ON ORBIT - PLANNED	●				89
EURECA (ESA)* (3 FLIGHTS)	PLANNED	●				91-92-->
INDUSTRIAL SPACE FACILITY (ISF)* (3 FLIGHTS PER YEAR)	PLANNED	●		●		92-->
SPACE FLYER UNIT (SFU)* - JAPAN	PLANNED	●				93
SPACE STATION	PLANNED	●	●	●	●	94-->
MAN TENDED FREE FLYER* (ESA)		●	●	●	●	97-->
LONG RANGE MISSIONS -LUNAR AND MARS INITIATIVES -MISSION TO PLANET EARTH -ROBOTIC EXPLORATION OF THE SOLAR SYSTEM	Under Consideration	|← TBD →|				LATE-90's -->

*REIMBURSABLE

Figure 8b

requirements are derived from the NASA Civil Needs Data Base (CNDB) which includes potential commercial and foreign missions; (Version 2.1, July 1987), the NASA mixed fleet manifest, and possible long-range missions being studied. The CNDB (currently being revised) is a data base used for transportation studies.

The Space Station era of satellite servicing begins with the on-orbit assembly of the Station, a major servicing achievement. Components of the Space Station will be carried to orbit by the STS beginning in 1994. The actual construction and operational verification of the Space Station requires the same servicing support elements that provide servicing capabilities for users. Specifically, assembly requires the ability to transport, manipulate, and mate numerous elements. Many of these same techniques will be used to repair, replace, and resupply early attached payloads. Studies will evaluate early attached payload requirements against the servicing capabilities as they are built-up over the Phase I period. Some of these attached payloads are referenced in Appendix A (OSSA Payload Summary charts).

The Space Station servicing functions required of the astronaut crew necessitates a combination of EVA and IVA that is enhanced by advanced robotics. Program planning anticipates 24 EVA man-hours from Shuttle-based Flights 1 through 10. There will be greater flexibility in EVA activities as these become Station-based after reaching Permanently Manned Capability (PMC).

The design for the core Station, platforms, payloads, and ground systems will consider baselining robotic assembly, maintenance, and servicing. To emphasize this directive, the Flight Telerobotic Servicer (FTS) is part of the first element launch to aid in the assembly of the Station. The FTS handles specific tasks for assembly, maintenance, inspection, and ORU change-out, and will be operable using both direct manipulator control and command sequences. Its design allows transport to different work sites as the Space Station develops. Additionally, Program plans stipulate employing the FTS for initial operations requiring telerobotic dexterous manipulation of attached payloads.

Assuming availability of a Vandenburg Shuttle launch, the baseline scenario for servicing the Polar Orbiting Platform (POP) consists of servicing at the Shuttle using the Remote Manipulator System (RMS), teleoperated end effectors, and EVA backup. This requires the POP to use its propulsion module to descend to Shuttle altitude. An alternate scenario requires servicing at mission altitude using the Shuttle, OMV, and the FTS.

Another piece of robotic servicing hardware on the manned station base is the Mobile Servicing Center. The MSC is an integrated system to support construction and assembly functions and features the U.S. provided mobile transporter and the Canadian-supplied interior and exterior control stations, an RMS, a special purpose dexterous manipulator (SPDM) for servicing tasks, and an MSC maintenance depot that holds tools and attachments. The MSC capabilities are added as the hardware arrives during the assembly sequence. Early functions include the capabilities to perform assembly tasks, maintenance and servicing, EVA support, orbiter docking, and the transport and servicing of attached payloads on external structures. Plans are to improve the MSC mobility on the truss structure around the Station. Two years after first element launch, the SPDM will provide end effector capabilities complementary to the FTS. The final addition of the maintenance depot provides the storage capability for the tools and attachments necessary to service the MSC.

When the Station achieves a permanently manned capability, servicing will become based at the Station with resupply for the Station and its payloads continuing as an STS service. In the steady state operational mode, (after completion of the baseline Station) all servicing and logistics needs will be accommodated within the planned five Shuttle-equivalent flights/year envelope.

Chapter 5: User Plans (Coordination of Current Activities)

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o ***All potential users of satellite servicing capabilities including civilian, defense, private, and foreign satellites and space vehicles:***

Since on-orbit servicing is currently heavily dependent on human intervention, only two national space programs, those of the U.S. and the U.S.S.R. can undertake such activities. Both the European and Japanese programs, however, are being directed toward the development of servicing capability as an integral activity within future manned space programs.

NASA satellite servicing activities are currently internally coordinated through the Office of Space Flight (OSF). NASA's Office of Space Flight is currently developing a Satellite Servicing Management Plan to establish agency policy and provide guidelines for implementation of servicing policy at individual program levels within NASA and other U.S. agencies, in addition to providing for interaction with potential commercial users. In addition, the NASA Satellite Servicing Steering Committee provides coordination between the various NASA offices involved with servicing activities to ensure that the requirements of the various NASA user organizations are being met, and that servicing activities are not being duplicated. The Satellite Servicing Working Group, with representatives from all of the NASA field activities engaged in satellite servicing, periodically reviews the progress on servicing developments which are under way and provides input to NASA Headquarters.

For coordination with external parties involved in satellite servicing activities, NASA relies on two mechanisms. The NASA/DoD On-Orbit Maintenance Working Group established under the Memorandum of Agreement coordinates servicing activities between NASA and the DoD. External satellite servicing coordination is sponsored by the Office of Space Flight through periodic satellite servicing workshops. These workshops are the mechanism by which NASA communicates its servicing progress and future plans to industry and the greater user community.

The most recent of these workshops, the Satellite Servicing Workshop III, was held at Goddard Space Flight Center on June 9-11, 1987. In addition to this comprehensive OSF-sponsored workshop, the NASA Space Station Office hosted robotics demonstrations at Goddard Space Flight Center on June 22-24, 1987 as part of a tour presented in conjunction with the American Institute of Aeronautics and Astronautics (AIAA) Space Station Conference. A total of eight demonstrations of the advanced robotic systems technology being evaluated for use on the Space Station were held for various audiences including AIAA members, Goddard management and employees, and the general public.

NASA activities in these areas ensure that appropriate servicing data is readily available to potential users so that each user may make an educated and informed decision regarding their use of servicing. Tool catalogues and capability documents currently in use are being updated and NASA plans to soon publish revised versions. Ultimately, users will avail themselves of on-orbit servicing when it makes programmatic sense, and each case will be considered individually. NASA will help non-NASA users to understand programmatic tradeoffs and will make available to them, on a cost-reimbursable basis, the general kinds of support and equipment needed.

o The pertinence of satellite servicing to insurance, including the character, cost and availability of insurance.

Present day satellite insurance policies pay the insurer up to a specified value for the total or partial loss of a satellite. Each policy is unique, i.e., a singular agreement between insurer and insured. Coverage provided mandates mitigation of damages in the event of loss and salvage rights in favor of insurers where, in some instances, insurers actually take title to the satellite. Consequently, repair or retrieval is desirable in cases where technically and economically feasible, with the insurers often making the ultimate decision.*

Insurance coverage is available for two separate phases of a satellite's life: launch and on-orbit operation. A leading underwriting institution has stated it would look favorably upon designs for improved repairability and retrievability, but cannot require satellite manufacturers to incorporate these features. Should these capabilities be included, they could produce reductions in insurance premiums for both phases. This could be achieved through the moderation of loss costs associated with possible failures, i.e., reducing what would otherwise be a total loss for an unrepairable and therefore unusable satellite to a partial loss. This would be accomplished by restoring all or a portion of the capability of such a satellite through on-orbit repair or retrieval.

The Palapa and Westar retrievals and the SYNCOM IV-3 on-orbit repair demonstrated to the insurance industry that the capability to service spacecraft in low Earth orbit accessible by Shuttle has been established. Consequently, one underwriter, as a result of this experience, has established in its insurance coverages the following requirement -- that the insured exercise all available means within reason to salvage a satellite that has either failed to reach orbit or that has failed in orbit. To the extent Shuttle-based servicing operations were available, insureds could have an increased ability to meet this requirement where satellites are stranded in low Earth orbit, or are capable of being de-orbited to low Earth orbit from a higher orbit. There is no current impact on insurance in the case of geosynchronous satellites or satellites unable to be placed in Shuttle-accessible orbit since transportation for servicing is not yet available.

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*This and other information regarding satellite insurance policies throughout Chapter 6 is derived primarily from the office of the Vice President of INTEC (International Technology Underwriters) in Washington, D.C.

Proposed serviceable commercial space platforms could greatly impact future insurance coverages. This coverage is unique and subject, moreover, to negotiation between the parties. Certain basic coverages specifically tailored for these platforms are envisioned; for example, property coverage for asset values, liability coverage for damage to third parties, and liability coverage for product malfunctions. These insurance coverages will be related to the types of servicing to be conducted; therefore, their requirements will be specifically tailored to the ultimate use of the facility.

Insurance underwriters, when establishing rates, do analyze the partial loss versus total loss components. This information is calculated in terms of loss failure probabilities and in terms of monetary impact associated with projected failure scenarios. The addition of servicing enhancements can work toward reducing failure probabilities and the associated costs for failures. This would impact both launch insurance coverages to the extent those coverages included satellite initial operations, and on-orbit coverages to the extent the satellites could be accessed.

The insurance issue, it should be noted, does not impact U.S. government spacecraft since all government payloads are self-insuring. The potential for total loss to the Government would be reduced if the spacecraft were serviceable in the event of failure.

o The prices to be charged for satellite servicing such that the full cost of such servicing can be recovered.

In August 1986, President Reagan directed that NASA shall no longer provide launch services for commercial and foreign payloads unless those payloads have unique, specific reasons to be launched aboard Shuttle. Accordingly, the Space Transportation System (STS) will launch only payloads that are Shuttle unique or have national security or foreign policy implications.

NASA may still launch those payloads which conform to the above noted 1986 decision, including the provision of Shuttle-unique services for on-orbit spacecraft. Therefore, a pricing policy both for launching and servicing of commercial and foreign payloads is still a requirement.

NASA's experience to date in pricing satellite servicing for commercial customers consists of the Palapa B-2 and Westar VI retrievals on STS 51-A, the attempted repair of SYNCOM IV-3 on STS 51-D, and its subsequent successful repair on STS 51-I. These satellites had experienced upper stage failures immediately following their deployment from the Shuttle. The charge for Palapa and Westar retrievals totaled $5.5M, and the charge for SYNCOM repair totaled $8.5M. At the time that services were priced for the Palapa, Westar, and SYNCOM satellites, NASA was strongly interested in demonstrating its Shuttle-based servicing capabilities. The servicing charges were determined on an additive cost basis. The costs which were included were those associated with mission planning, development of unique hardware, integration, training, and revisit/retrieval.

A proposed satellite servicing pricing policy presented in the NASA Report to Congress, December 1986, entitled "On-Orbit Service, Repair, and Recovery of Spacecraft Report," was based on pre-51-L STS data. This policy contains three costing elements: transportation, a tailored package of services, and additional optional services. This pricing policy was based on full cost recovery and included pro rata costs of transportation, the costs of using any servicing tools and capabilities (such as EVA, MMUs, OMVs, etc.), and the costs of any non-standard optional services, including the full, rather than additive, costs of any mission-unique hardware. Satellite servicing missions priced on a full cost recovery basis, will result in prices exceeding those charged for the prototype repair missions on STS 51-A, D, and I.

Previous pricing algorithms for Shuttle services, including satellite servicing, used factors which have changed significantly over the past two years. The two primary factors which will affect future Shuttle pricing are: a projected Shuttle flight rate which is reduced from earlier projections, and a recently announced and significant increase in downweight capability of the orbiter. Because Shuttle flight cost is a major element in pricing a retrieval mission, the current retrieval/revisit pricing policy is being reformulated to reflect these changes.

Policy has not yet been established for pricing of Space Station supplied servicing. It is NASA's intent, in accordance with the civil space policy, to seek full cost recovery for pricing of Shuttle servicing.

Chapter 8: Goals and Objectives

o "The Administrator shall conduct a thorough and comprehensive study of satellite servicing with a view toward establishing national goals and objectives for utilizing such capabilities."*

Satellite servicing is a technologically evolving activity which has not yet attained final stages of development. Progressing from a contingency reaction to a baselined activity within many user programs, the intent of servicing is to extend operational life, enhance capabilities, and decrease system life-cycle costs. Servicing is currently constrained to Shuttle accessible orbits, but it will evolve to include Space Station based activities and remote operations with robots in support of permanent long-term operations in space. Developments are proceeding rapidly in the international arena; for example, (1) the Federal Republic of Germany will demonstrate robotic operations on an upcoming Spacelab flight; (2) Canada is developing the technology for a Mobile Servicing Center on the Station; and (3) Japan is developing the technology for remote servicing from expendable launch vehicles.

In keeping with the information noted above, NASA proposes that the development of appropriate satellite servicing capabilities to enhance and protect national capital investments in space systems be considered and subsequently adopted as a national goal. With this in mind, NASA presents the following agency objectives for utilizing satellite servicing:

(1) To develop the technology, hardware, tools, facilities, and infrastructure to meet projected NASA servicing requirements;

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*Excerpted from the National Aeronautics and Space Administration Authorization Act of 1988, (H.R. 2782), Title 1, Sec. 118.

(2) To continue to strive towards efficiency (cost-effectiveness) in on-orbit servicing support through the development of general purpose tools and common systems and subsystems;

(3) To continue to evolve on-orbit servicing capabilities, including development of telerobotic and robotic servicing systems, to support servicing at remote sites;

(4) To support servicing needs of DoD, domestic commercial, and foreign space communities upon appropriate request;

(5) To promote the spinoff of commercial services;

(6) To develop and promote the use of servicing interface standards;

(7) To stimulate the technology base in universities and industry; and

(8) To utilize commercially available on-orbit servicing to the fullest extent feasible, and avoid actions that may preclude or deter commercial space sector activities except as required by national security or public safety.

APPENDIX A

OSSA PAYLOADS

This appendix presents a compilation of on-orbit servicing information concerning payloads selected by OSSA as potential drivers for the establishment of servicing requirements at the Space Station. The data was extracted from "OSSA Space Station Servicing Book II", published on November 30, 1987. The information is presented in two summary tables.

Table A-1, "OSSA Payload Summary," lists the payload by abbreviation. The full name of each payload is provided within a column which also includes a brief description of the payload. A summary of the servicing activities for the payload appears in the last column. The second column indicates whether the payload is on attached payload (A), a free-flyer (FF), a polar platform (P), a co-orbiting platform (C), or a laboratory module (L).

As a rough measure of the degree of payload definition, the current phase of development of each payload is indicated in column 3. The categories are Pre-phase A (Pre-A), Phase A, Phase B, and Phase C/D. Pre-phase A is the conceptual study phase in which requirements documents are produced identifying scientific objectives, technical concepts, and preliminary scoping. Phase A involves analysis of alternative system designs, preparation of a preliminary project plan, and feasibility studies. Phase B encompasses preliminary design and verification of critical systems and subsystems, and concludes with the choice of a single project approach and the development of a detailed schedule and procurement approach. Phase C/D refers to a stage where developmental funding as been approved and implemented.

The second table, "OSSA Payload Milestone and Servicing Schedule," shows the launch date, the date of first Space Station service, the servicing interval in months, and the expected operational lifetime of the payload. The shaded bars in the launch date column represent a time interval during which the payload is operational, and the leftmost border of the shaded bar falls in the year of launch.

OSSA PAYLOAD SUMMARY

PAYLOAD	TYPE	PHASE	DESCRIPTION	SERVICING
ASTRO	A	C/D	ASTRO applies ultraviolet imagery, spectroscopy & polarimetry to the study of faint objects.	None
ASTROMAG	A	PRE-A	Astrophysics Magnet Facility. Uses superconducting magnet for high energy Astrophysics.	*On-Orbit Assembly *Resupply Helium *Replace Science Instruments
ATF	A	PRE-A	Astrometric Telescope Facility. Optical telescope designed to search for planetary systems & support additional Astrophysics.	*On-Orbit Assembly *Replace Mechanical or Electronic Components
AXAF	FF	B	Advanced X-Ray Astrophysics Facility. The X-Ray Great Observatory.	*Changeout ORUs and Science Instruments
CDCE	A	A	Cosmic Dust Collection Experiment. Measures orbital parameters of impacting extraterrestrial material.	*Changeout Impacted Cells
CRNE	A	C/D	Cosmic Ray Nuclei Experiment. Studies energy spectra and propagation of Cosmic Rays. Electronic Counter Telescope.	None
Eos	P	A	Earth Observing System. Obtains detailed physical, chemical, & biological studies of earth & atmosphere through four polar platforms.	*ORU Changeout *Science Instrument Replacement
EP	FF	C/D	Explorer Platforms. Will carry various instrument packages to perform Astrophysics studies of a wide variety of objects.	*Changeout Science Instrument. First exchange is XTE for EUVE
GRO	FF	C/D	Gamma Ray Observatory. This Great Observatory will study gamma ray emitting objects.	*Replace 1000 kg of Hydrazine
HH/ERBE	A	PRE-A	Hitchhiker Earth Radiation Budget Experiment. Hitchhikers allow small science and engineering payloads to conduct their intended missions. ERBE investigates radiative output of the tropics over time.	None
HRSO	A	PRE-A	High Resolution Solar Observatory. Addresses fundamental solar phenomena.	*Replace co-observing ultraviolet science instrument
HST	FF	C/D	Hubble Space Telescope. This visible light Great Observatory will allow study of objects up to 14 billion light years away.	*Changeout ORUs *Science Instrument Replacement
LAMAR	A	B	Large Area Modular Array. Performs sensitive cosmic x-ray observations in the 0.10 - 10.0 KEV energy range.	*Replace gas module.
LASERCOM	A	PRE-A	Laser Communications Engineering Test. Tests acquisition and tracking with telescope, transmitter, and receiver.	None
LAWS	A	A	Laser Atmospheric Wind Sounder. Provides a direct measurement of the tropospheric wind field, via Doppler-LIDAR Techniques.	*Changeout of ORUs

OSSA PAYLOAD SUMMARY (continued)

PAYLOAD	TYPE	PHASE	DESCRIPTION	SERVICING
LDR	FF	PRE-A	Large Deployable Reflector. Will conduct submillimiter-infrared astronomical observation of various astrophysical phenomena in the 30 - 1000 micron region.	*On-orbit assembly *Replenish liquid helium
LSRF	L	A	Life Sciences Research Facility. Pressurized module which will provide a laboratory in space for basic research in the Life Sciences.	*Resupply of consumables and removable of waste
MMPF	L	A	Microgravity & Material Processing Facility Pressurized module which provides opportunities to process very pure & new forms of materials in a controlled microgravity environment.	*Resupply of consumables and removable of waste
PIMS	A	A	Plasma Interaction Monitoring System. Measures induced space environment around the Space Station and the interactive effects between the Space Station and this enivronment.	None
POF	A	A	Pinhole Occulter Facility. Uses x-ray & corna-graph equipment to study plasma dynamics.	*Changeout two proportional counters
SBAR	A + FF	PRE-A	Space-Based Antenna Range. Will test experimental communications links, antenna characteristics, & other functions of spacecraft prior to final orbit placement.	*Changeout test instrument & subsystem modules *Replenishment of hydrazine
SIRTF	FF	A	Space Infrared Telescope Facility. This Great Observatory will study astrophysical features / phenomena in the infrared region.	*Resupply liquid helium *Replace ORUs
SRI	A	PRE-A	Search and Rescue Instruments	*TBD
3S	FF	PRE-A	Space Station Spartan. This system is a relatively low cost system which allows free flying missions to originate from SS.	*Changeout of science Instrument *Replenish hydrazine *Changeout ORUs
STO / PIG	A + FF	A	Solar Terrestrial Observatory: Plasma Instrument Group. See STO / SS.	*Replace ORUs Replenish Gas
STO / POP	P	A	Solar Terrestrial Observatory: Polar Orbiting Platform. See STO / SS.	*Replace ORUs Replenish Gas
STO / SIG	A + FF	A	Solar Terrestrial Observatory: Solar Instrument Group. See STO / SS.	*Replace ORUs *Replace film cannisters
STO / SS	A + FF	A	Solar Terrestrial Observatory: Space Station. Has a variety of instruments to study solar activity & the physical processes coupling the atmosphere, the magnetosphere, & the sun.	*Changeout ORUs *Replace Film
TRIS	A	A	Tropical Region Imaging Spectrometer. Studies biological & physical processes of tropical regions	*Replace ORUs (cooling system)
TRMM	A	A	Tropical Rainfall Measurement Mission. Measures rain-fall in the tropics to increase our understanding of tropical energetic & hydrologic processes.	None
XGP	FF	PRE-A	Experimental GEO Platform. Allows development & demonstration of enabling communications & science payload & antenna technologies.	*Unfurl & test XGP at SS *Replenish hydrazine (in SITU) *Replace ORUs (in Situ)

A = Attached; C = Co-orbiting Platform; FF = Free-Flyer;
L = Laboratory; P = Polar Platform

C0361*7D-02

Table A-2: OSSA PAYLOAD MILESTONE AND SERVICING SCHEDULE

PAYLOAD	LAUNCH DATE													DATE OF FIRST SERVICE													SERVICING INTERVAL (MTHS)		OPERATIONAL LIFETIME (YRS)
	89	90	91	92	93	94	95	96	97	98	99	00	01	89	90	91	92	93	94	95	96	97	98	99	00	01	STS	SS	
ASTRO ▨	TBD													N/A													N/A		1
ASTROMAG								■	■	■	■	■	■								●							12 - 24	6 - 8
ATF								■	■	■	■	■	■								●							60	20
AXAF							■	■	■	■	■	■	■										●					30 - 60	15
CDCE ▨						■	■	■	■	■										●								6	5
CRNE						■	■							N/A													N/A		2
EOS / NPOP-1							■	■	■	■	■	■	■										●				36/PLATFORM		15 / PLATFORM
EOS / NPOP-2									■	■	■	■	■												●		36/PLATFORM		15 / PLATFORM
EP ▨			■	■	■	■	■	■	■	■	■	■	■					●									24	24	10
GRO ▨		■	■	■	■	▨ WITH REBOOST	▨	▨	▨										●									48	4 / 8
HH/ERBE							■	■	■	■	■			N/A													N/A		5
HRSO	TBD													TBD														12	3
HST ▨	■	■	■	■	■	■	■	■	■	■	■	■	■				●										36	18 - 22	15
LAMAR	TBD													LIFT OFF + 3 YEARS														36	TBD
LASERCOM							■							N/A													N/A		1/2 - 1
LAWS										■	■	■	■													●		36	5
LDR												■	■												●			24	15
LSRF							■	■	■	■	■	■	■							●								3	20 - 30
MMPF							■	■	■	■	■	■	■							●								1, 3	20 - 30
PIMS						■	■	■	■	■	▨	▨ TBD	▨	N/A													N/A		> 5
POF								■	■	■	■	■	■											●				60	15
SBAR	TBD																					●						6	INDEFINITE
SIRTF								■	■	■	■	■	■										●					18 FIRST, 27 AFTER	10
SMM RETRIEVAL		■													●												N/A		N/A
SRI	TBD													TBD													TBD		TBD
3S							▨	▨	▨	▨ TBD	▨	▨	▨								●							4 or 6	TBD
STO / PIG						■	■	■	■										●									3	4
STO / POP-1						■	■	■	■											●							1		4
STO / POP-2											■	■	■												●		1		4 - 6
STO-SIG						■	■	■	■										●									3	4
STO-SS						■	■	■	■										●									3	4
TRIS							▨	▨	▨	▨ TBD	▨	▨	▨										●					36	TBD
TRMM	TBD													N/A													N/A		3
XGP										■	■	■	■										●					3	20

.*Note: Many of the mid and long term payloads are still in the planning and development stage and have not yet been approved for development.
See Table A-1 for the phase of each payload. Source (for all except SMM Retrieval): OSSA Space Station Servicing Data Book II (Nov. 30, 1987).
▨ Indicates approved payload.

APPENDIX B

BIBLIOGRAPHY

1) E. Falkenhayn, "The NASA/GSFC MMS Experience," NASA/Goddard Space Flight Center, working paper, December 1987.

2) R. Turnill, Jane's Spaceflight Directory 1987, Jane's Publishing Inc., New York, New York, 1987.

3) OSSA Space Station Servicing Data Book II, Parts I and II, NASA/OSSA, BDM Corporation, BDM/COL-87-0910-TR, November 30, 1987.

4) S. Ride, Leadership and America's Future in Space, a report to the NASA Administrator, August, 1987.

5) "Servicer System Users Guide," Report MCR-86-1339, Martin Marietta, NASA Contract NAS 835625 for MSFC, p. 1-1, July 1986.

6) W. DeRocher, Jr., "Spacecraft Design for Servicing," Proceedings of Satellite Services Workshop II, Volume I, pp. 34-49, November 6-8, 1985 at JSC.

7) National Space Transportation and Support Study Civil Needs Data Base, Version 2.1, Volumes II and III, NASA/MD, July 16, 1987.

8) "On-Orbit Service, Repair, and Recovery of Spacecraft Report," NASA Office of Commercial Programs, Report to Congress, December 19, 1986.

9) Satellite Servicing Workshop III Proceedings, Sessions I-V, NASA/Goddard Space Flight Center, June 9-11, 1987.

10) Space Assembly Maintenance and Servicing Study, Final Report, Volumes I-V, Lockheed Missiles and Space Co., LMSC-F104866, June 1987.

11) Letter from John B. Higginbotham, Vice President of INTEC, International Technology Underwriters, to Bob Tucker, NASA Code MC, November 19, 1987.

12) L. Norton, "Preliminary Integrated Operations Scenarios Space Station," Mission Support Directorate, Mission Planning and Analysis Division, JSC-32040, 87-FM-12, Draft Review Copy, July 1987.

APPENDIX C

ACRONYM LIST

AIAA	American Institute of Aeronautics and Astronautics
AXAF	Advanced X-Ray Astrophysics Facility
CCTV	Closed Circuit TV, Voice Controlled
CNDB	Civil Needs Data Base
DoD	Department of Defense
EASE/ACCESS	Experimental Assembly of Structures in EVA/Assembly Concept for Construction of Erectable Structures
ELV	Expendable Launch Vehicles
EOS	Earth Observing System
ESA	European Space Agency
EVA	Extravehicular Activity
FSS	Flight Support System
FTS	Flight Telerobotic System
GRO	Gamma Ray Observatory
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
ISF	Industrial Space Facility
IVA	Intravehicular Activity
KSC	John F. Kennedy Space Center
LDEF	Long Duration Exposure Facility
MMS	Multimission Modular Spacecraft
MMU	Manned Maneuvering Unit
MOA	Memorandum of Agreement
MSC	Mobile Servicing Center
MSFC	George C. Marshall Space Flight Center
MST	Module Service Tool
MTFF	Man-Tended Free Flyer
NASA	National Aeronautics and Space Administration
NSDD	National Security Decision Directive
OMV	Orbital Maneuvering Vehicle
ORU	Orbital Replacement Unit
OSF	Office of Space Flight

OSSA	Office of Space Science and Applications
OTV	Orbital Transfer Vehicle
PAM	Payload Assist Module
PMC	Permanently Manned Capability
POP	Polar Orbiting Platform
RMS	Remote Manipulator System
SAMSS	Space Assembly, Maintenance, and Servicing Study
SFU	Space Flyer Unit
SHOOT	Superfluid Helium On-Orbit Transfer
SIC	Standard Interface Connectors
SIRTF	Space Infra-Red Telescope Facility
SMM	Solar Maximum Mission
SPDM	Special Purpose Dexterous Manipulator
STS	Space Transportation System

NASA
National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

MAR 24 1988

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

The enclosed report, "Launching Payloads by Means of Expendable Launch Vehicles," has been prepared in response to the provisions of Section 116 of the National Aeronautics and Space Administration Authorization Act of 1988 (P.L. 100-147). Section 116 stated that it is the sense of the Congress that "...a diversified family of expendable launch vehicles be incorporated into the Nation's civilian space program," and directed that NASA report on actions taken to ensure that expendable launch vehicles or, if available, commercial launch services be obtained for the launch of a series of specific payloads.

I, or my staff, would be pleased to discuss this report with you further, if you wish.

Sincerely,

James C. Fletcher
Administrator

Enclosure

cc: Honorable Manuel Lujan, Jr.

LAUNCHING PAYLOADS BY MEANS OF EXPENDABLE LAUNCH VEHICLES

REPORT TO

COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

AND

COMMITTEE ON COMMERCE, SCIENCE AND TRANSPORTATION
UNITED STATES SENATE

REPORT TO I. INTRODUCTION

The National Aeronautics and Space Administration Authorization Act of 1988 (P.L. 100-147), dated October 30, 1987, requires that the NASA Administrator report to the Congress by January 15, 1988, on NASA's compliance with the provisions of Section 116. Section 116 states that it is the sense of the Congress that: "(a)... a diversified family of expendable launch vehicles be incorporated into the Nation's civilian space program. (b) the Administrator shall establish a program for launching payloads by means of expendable launch vehicles and, if available, by commercial launch services. (c) the Administrator shall take such action as may be necessary to ensure that expendable launch vehicles or, if available, commercial launch services are obtained for the launch of the following payloads:

(1) Roentgen Satellite (ROSAT), for launch in 1990.
(2) Tracking and Data Relay Satellite (TDRS-F), or a planetary mission.
(3) Extreme Ultraviolet Explorer (EUVE), for launch in 1991.
(4) Mars Observer, for launch in 1992."

The Authorization Act also included an amount of $60 million for Expendable Launch Vehicle operations. The FY 1988 Continuing Appropriations Act (P.L. 100-202) limited funding to $28 million for two Delta-Class vehicles for ROSAT and EUVE.

II. APPROACH

A. GENERAL

NASA has established a Mixed Fleet Space Transportation program composed of the Space Shuttle and Expendable Launch Vehicles (ELV's). The ELV side of this program will launch U.S. civil government payloads not requiring the unique capabilities of the Space Shuttle. NASA plans to acquire commercial ELV launch services competitively in several performance classes, whenever such services are available from industry. In procurement of these launch services, the requirements of the Competition In Contracting Act (CICA) will be strictly observed. The first phase of the program procures ELV's for five high priority spacecraft that were originally manifested near-term on the shuttle. They are already built and delivered and are to be matched to available ELV's. A total of seven ELV's will be utilized, because one spacecraft is to be redesigned and its experiment divided between three vehicles. A directed procurement process will be utilized for selection of these vehicles because of the need to launch these missions as soon as possible. Of the total of seven launch vehicles to be acquired, three will be acquired through the Department of Defense (DOD) and four directly from U.S. commercial operators.

NASA's testimony before the House Committee on Science, Space and Technology, Subcommittee on Space Science and Applications, on September 17, 1987, provides a full explanation of the phased implementation plan for procuring expendable launch vehicle services for NASA's needs. Further, NASA's ELV Mixed Fleet transitional plans for the first phase were provided to Congress on December 4, 1987, by the Determination and Finding Report containing the justification for other than full and open competition for seven launch vehicles.

B. PHASING OF IMPLEMENTATION PLAN

ELV launches for the ROSAT in 1990 and the EUVE in 1991, as specified in the Authorization Act, are being acquired through the DOD in accordance with a NASA/DOD Agreement, signed October 7, 1987, to exchange shuttle and ELV launch services on a quid-pro-quo basis. These two missions are being placed on USAF Delta-II vehicles. The third launch vehicle is a Titan-IV in support of either the Magellan, Galileo or Ulysses planetary mission manifested on the shuttle. The earliest requirement for the Titan-IV launch is May 1991, and it will be also be provided by the USAF on a quid-pro-quo exchange basis.

The four launch vehicles to be directly acquired from commercial operators in the transition phase include a Titan-III, an Atlas Centaur, and two Scouts. Use of the commercial Titan-III vehicle has been evaluated for launch of TDRS-F and the Mars Observer. Study and analysis over the past several months indicates that there are still some technical and cost uncertainties involved in placing the TDRS spacecraft on an ELV. The problem relates primarily to the fact that the expendable vehicle places greater loads on the spacecraft, which was designed to take advantage of the more moderate launch environment provided by the Space Shuttle. The primary concern involves potential damage to the delicate TDRS antenna system as a result of these greater launch loads.

At the same time, analysis indicates that the Mars Observer spacecraft is basically compatible with launch on a Titan III, but that modifications to the transfer orbit stage would be required. Launching the Mars Observer on an ELV would have the benefit of permitting use of the Shuttle flight now planned for that mission for another spacecraft. Launch of TDRS-F on the Shuttle would hold that spacecraft to a launch environment that it has successfully experienced before and also would permit full loading of the spacecraft fuel tanks, providing a potential for longer on-orbit lifetime. Given the present uncertainty of available appropriations, NASA plans to maintain a dual compatibility option for the Mars Observer, pending further Congressional indication of funding feasibility for the Titan III. If funding were provided, NASA would acquire the Titan III directly from the Martin Marietta Corporation.

The Atlas/Centaur launch service is being considered in the transition phase for acquisition commercially for the Combined Release and Radiation Effects Satellite (CRRES) to be launched in 1990. We are currently discussing with General Dynamics Corporation an exchange of residual Atlas/Centaur and Shuttle/Centaur assets for launch services for this mission. Several of the planned experiments, however, could not be accommodated on an Atlas Centaur launch, but could be accommodated by the launch of small payloads on two Scout vehicles.

Initial funding for the two Delta-II's is in the NASA FY 1988 budget. Funding for the Titans, Atlas/Centaur and Scouts is included in NASA's FY 1989 budget request to Congress.

For launches beyond the transitional period, 1992 and beyond, it would be our intent to competitively procure launch services in four performance classes from commercial operators where the opportunity exists. Launch services capabilities will be established for the U.S. civil government community in small (Scout class), medium (Delta class), intermediate (Atlas/Centaur/Titan-III class), and large (Titan-IV class) classes. In all performance classes, with the exception of the large class (Titan-IV), we expect viable commercial competition. In this class, we would expect to continue to contract through the DOD, since Titan IV's are not available commercially and there are no other vehicles in its capability range on which to base a competition. We can project overall requirements for the future on the order of approximately two small class launches per year, three to five in the medium class, and one to two in the intermediate and large classes.

III. SUMMARY

NASA is taking action in response to the direction of the Congress in the NASA Authorization Act of 1988 within the constraints of the FY 1988 Continuing Appropriation and a reasonable projection for future years. Where possible, commercial launch services are being acquired in the early transitional phase. Following this ELV startup phase, NASA will compete the procurement for launch services wherever the opportunity exists in the United States.

NASA

INTERNATIONAL SPACECRAFT DOCKING STUDY

A REPORT TO CONGRESS

OFFICE OF SPACE FLIGHT
WASHINGTON, D.C.

APRIL 1988

Preface

NASA has prepared the following report in response to a request by the U.S. House of Representatives Committee on Science, Space, and Technology to *"...undertake a conceptual study of the potential uses for, engineering approaches to, and cost of a universal docking module that could be employed on the Space Station, Space Shuttle, Soviet manned spacecraft, and future manned space systems developed by all nations.* The request was made in July 1987 in the Committee's report (#100-204) accompanying H.R. 2782, the NASA Authorization Act for Fiscal Year 1988.

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Executive Summary

Two methods can be employed to mate spacecraft: docking and berthing. Docking is the joining of two spacecraft by directly maneuvering one craft into contact with the other at a chosen interface. Berthing is defined as the joining of two spacecraft using a manipulator or other mechanical device to move one into contact (or very close proximity) with the other at a chosen interface. Because it tends to be less complicated than berthing, this study focused on docking to implement cooperative missions requiring physical linkage.

NASA, however, has employed both methods. The Apollo Command Service Module and Lunar Module used a docking system. The retrieval of the Solar Max Mission satellite by the Space Shuttle was accomplished via berthing. One of the more noteworthy examples of docking was the Apollo/Soyuz Test Project (ASTP) which culminated in July 1975 with the coupling of a U.S. Apollo and Soviet Soyuz spacecraft. Since ASTP, there has been no requirement for the U.S. to carry out docking of spacecraft. With the advent of the Space Station this will change, and a number of Shuttle/Station docking options are under review.

A spacecraft docking operation consists of four phases: rendezvous, approach, docking mechanism operation, and separation. The target spacecraft remains passive while the active chaser spacecraft performs all required maneuvers. Docking is a complex operation involving many systems and mechanisms on both spacecraft as well as ground systems. An obvious but important point is that the least maneuverable spacecraft will generally set the requirements for mission planning and docking mechanism design.

This study did not attempt to project or define the potential missions of the future that might be candidates for docking and a universal docking system. Instead, it identified broad types of manned spacecraft missions that could form the basis of international cooperation requiring docking capabilities. These mission types are personnel rescue, spacecraft rescue, scientific experiments and research, direct supply and personnel launch and delivery, orbital transfer, return to earth, commercial ventures, and spacecraft assembly/construction. The study then considered specific manned spacecraft (such as the U.S. Space Shuttle, the European Space Agency's planned Hermes spacecraft and the Soviet MIR space station) in order to bound the analysis and focus the study. With both potential missions and spacecraft identified, the study examined "mission practicality factors," factors which shape what is possible and practical. Among these factors are spacecraft launch considerations, orbital maneuvering capability and spacecraft hatch size. The critical nature of such technical factors is illustrated by the geography of existing launch sites, a spacecraft launch consideration. While U.S. spacecraft can reach all Soviet and European Space Agency (ESA) orbits inclined greater that 28.5°, Soviet spacecraft can reach only U.S. and ESA orbits inclined greater than approximately 40°. Which means that a Soviet-launched rescue mission to the U.S. Space Station would be in most cases impossible to achieve, because the Station will orbit the Earth at an inclination of 28.5°.

To enable maximum possible cooperation in space, all present and future manned spacecraft would have to be equipped with a standardized docking mechanism. However, given the wide disparity in spacecraft designs, an international agreement on such a mechanism would be required. NASA thus believes that a practical approach would be to establish a set of international docking interface standards. This would enable each nation or organization to develop its own docking mechanisms that incorporate the international interface. With this approach, the ability to dock within certain performance standards is assured, but each nation or organization is free to tailor the design of its docking mechanism to fit its own individual spacecraft, spaceflight hardware design philosophies, and unique cooperative mission requirements. The emphasis is on interface standards rather than hardware design mechanisms. This approach is a flexible one. It is also a proven approach, for it was used successfully by the U.S. and the Soviet Union in the ASTP program.

If such an approach is pursued, the cost to the U.S. would be based on the costs of developing a specific docking mechanism in addition to modifying the Space Shuttle, as it is the only U.S. spacecraft at present that could utilize a docking capability. The cost of such an undertaking would be significant. Utilizing ASTP data with adjustments for complexity, quantity and contractor expenses, NASA estimates the costs to be on the order of $300 million in Fiscal Year 1988 dollars. This is a preliminary estimate only. A more precise estimate could be made only with more detailed design information.

Spacecraft Docking Terminology

To assist the reader with an understanding of terminology used throughout the report, the following definitions are provided:

Androgynous Interface: a non-polar interface; one which can physically join with another of the same design.

Berthing: The joining of two spacecraft using a manipulator, or other mechanical device, to move one into contact (or very close proximity) with the other at a chosen interface.

Chaser Spacecraft: The spacecraft that performs the maneuvers in rendezvous and proximity operations.

Continuously-Manned Spacecraft: A spacecraft that has accommodations for continuous habitation during its mission.

Docking: The joining of two spacecraft by independently maneuvering one into contact with the other at a chosen interface.

Docking Interface: The area of contact between two docking mechanisms.

Docking Mechanism: A mechanism that performs functions to connect one spacecraft to another in a docking operation.

Docking Module: A structural element which provides a support and attachment interface between a docking mechanism and a spacecraft.

Drogue: A spacecraft docking receptacle which captures the probe of another spacecraft.

Global Positioning System (GPS): A satellite system designed to provide position determination; that is, position information in low Earth orbit and on the surface of the Earth.

Launch Azimuth: The measure of the angle between due north and the direction in which a spacecraft is launched.

Launch Window: The time span during which a launch may be made to satisfy some mission objective. Usually a short period of time each day for a certain number of days.

Man-Tended Spacecraft: A spacecraft that has accommodations for only temporary habitation during its mission.

Mating: The physical joining of two spacecraft through either a docking or berthing process.

Orbit Inclination: The angle between an orbital plane and the earth's equatorial plane.

Probe: An extended structure on one spacecraft which is inserted into a compatible receptacle (drogue) on another spacecraft, creating a linkage (docking) of the two spacecraft.

Relative State: The position and motion of one spacecraft relative to another.

Proximity Operations: The operations, or maneuvers, designed to bring two spacecraft into close proximity following rendezvous; also the maneuvers used to initially separate two spacecraft at the conclusion of a mission.

Rendezvous; Rendezvous Operations: The bringing together of two spacecraft at a chosen orbital location.

Space Station: A continuously-manned spacecraft which is designed to remain in orbit.

Stationkeeping: The act of keeping two spacecraft in constant position relative to each other.

Target Spacecraft: The non-maneuvering spacecraft in rendezvous and proximity operations.

Translation: Straightline motion of a spacecraft.

Introduction

In order to plan and develop international manned space missions that may utilize docking mechanisms, a number of factors must be considered. Desired mission/spacecraft combinations must first be identified and prioritized, and mission practicality assessed, since some missions involving two particular spacecraft may prove difficult or impossible to execute. Only then can decisions be made regarding the methods to be used in joining the spacecraft, mission plans, and design of the required equipment. Primary variables involved in making those decisions will include mission objectives, individual spacecraft capabilities and design, mission/spacecraft priorities, and available resources.

NASA study participants investigated only the technical aspects of cooperative missions; areas addressing foreign policy and domestic policy, such as mission and budget priorities, are not discussed. The study, although addressing general considerations of all operations and equipment required to perform spacecraft rendezvous and docking, is limited in detailed analysis to docking mechanisms. The docking mechanisms are perhaps the most vital part of cooperative missions since they are the point of physical contact between spacecraft; as such, they must be designed to meet standardized requirements.

The terms "docking mechanism" and "docking module" are often used interchangeably, but they correctly refer to two completely different types of equipment. A docking mechanism is a device designed to contact, capture, and rigidly connect to a corresponding docking mechanism on a second spacecraft. A docking module, on the other hand, is typically a structural adapter element designed to provide a support and attachment point on a spacecraft for the docking mechanism. Other functions, such as provision for airlock capability, can also be incorporated into a docking module, if needed. It should be pointed out that it is unlikely that a standardized docking module could be defined at this time for future cooperative missions due to the significant configuration and structural differences between the various existing and planned manned spacecraft.

While it is believed that standardization of some docking system elements other than the mechanism is possible, practical considerations suggest that the docking mechanism offers the most likely opportunity for international standardization. This is supported by experience gained from the Apollo-Soyuz Test Project. Due to the many dissimilarities between the Apollo and Soyuz spacecraft, the docking mechanism proved to be the only realistic area for hardware or system standardization. A similar situation can be expected in future international cooperative mission development.

In keeping with these criteria, four major areas of study were established: first, the identification of potential uses for international space missions and applicable U.S. and foreign spacecraft; second, the development of design requirements for spacecraft docking mechanisms to support the identified uses and applicable spacecraft; third, conceptual design of international docking mechanisms; fourth, estimation of costs to the U.S. for international docking mechanisms for use on the Space Shuttle and Space Station.

Chapter 1: Background and History

SPACECRAFT MATING METHODS

The following information is presented in order to acquaint the reader in a general way with the operational procedures associated with spacecraft docking on-orbit.

Manned spacecraft can participate in cooperative missions in a number of ways. Spacecraft need not be physically joined; stationkeeping spacecraft can exchange packages and spacesuited personnel by using manipulators, Manned Maneuvering Units (MMUs), or transfer spacecraft such as the Orbital Maneuvering Vehicle (OMV). However, structurally joining spacecraft in a manner that provides a pressurized personnel transfer capability gives the greatest amount of mission capability and flexibility -- personnel can transfer without the hazards of Extra-Vehicular Activity (EVA); small packages can be transferred through the pressurized passageway without exposure to the space environment; externally-carried packages can be exchanged using manipulators or by EVA personnel in a safer, more reliable fashion than between stationkeeping spacecraft.

Two methods can be employed to physically join, or mate spacecraft: docking and berthing. Docking is defined as the joining of two spacecraft by directly maneuvering one into contact with the other at a chosen interface. Examples are the U.S. Apollo Command/Service Module-to-Lunar Module and Soviet Soyuz-to-Mir Space Station dockings. Berthing is defined as the joining of two spacecraft using a manipulator or other mechanical device to move one into contact (or very close proximity) with the other at a chosen interface. An example is the retrieval of the Solar Maximum Mission Satellite by the Space Shuttle using its Remote Manipulator System during STS Mission 41-C.

Depending on the spacecraft involved and the manipulator used, the interface contact velocities and misalignments for docking and berthing may be very different. Consequently, an interface mechanism optimized for berthing may not work for docking, and vice versa.

Even if berthing is used to join two spacecraft, there must still be a docking mechanism at the mating interface to hold them securely together. Since the docking mechanism is both a necessary and sufficient design for docking operations, and since the addition of a berthing mechanism increases the complexity of the system, only docking operations were specifically investigated in the study as a way to implement cooperative missions requiring physical linkage. However, while docking can fulfill most, if not all cooperative mission spacecraft mating requirements, alternatives exist which may be better or more cost-effective for a given mission and/or combination of spacecraft.

HISTORY

The first spacecraft docking occurred over 22 years ago when on March 16, 1966, the Gemini VIII spacecraft docked with an unmanned Agena target vehicle. Gemini/Agena dockings were performed in all four subsequent Gemini missions.

Docking was one of the key features of the mission profile in the Apollo Lunar Landing Program. Two separate dockings were required on every lunar mission. During the transit to the moon, the Command/Service Module had to first dock with the stowed Lunar Module in order to remove it from the Saturn rocket third stage. A second docking was required when the Lunar Module Ascent Stage reached lunar orbit at the conclusion of the surface activities. The first Apollo dockings took place in Earth orbit in March 1969, on the Apollo 9 mission.

The Apollo docking system (Fig. 1.1), consisted of a probe assembly mounted to the Command Module and a corresponding drogue located on the Lunar Module. Once the spacecraft were docked, the probe and drogue were removed, clearing a passageway. The Apollo docking system was also used during the Skylab program in the early 1970's. Although difficulties were sometimes encountered, the system operated successfully on all of the Apollo and Skylab missions.

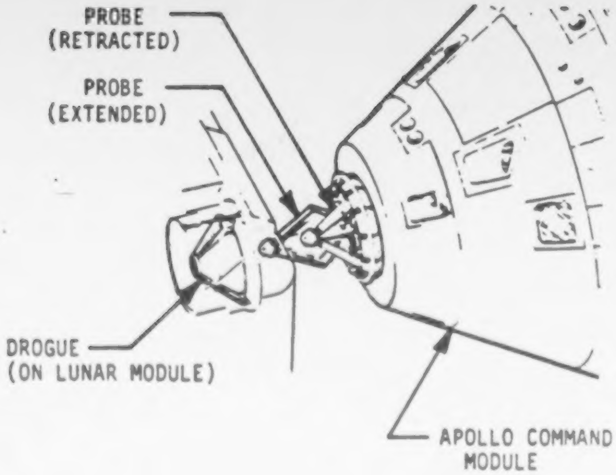
PROBE
(RETRACTED)
PROBE
(EXTENDED)
DROGUE
(ON LUNAR MODULE)
APOLLO COMMAND
MODULE

FIGURE 1.1 APOLLO DOCKING SYSTEM

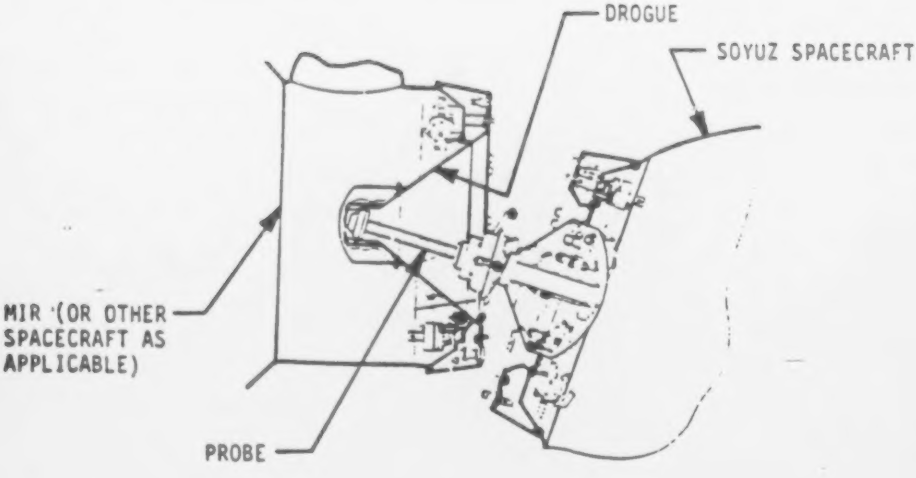
DROGUE
SOYUZ SPACECRAFT
MIR (OR OTHER
SPACECRAFT AS
APPLICABLE)
PROBE

FIGURE 1.2 SOVIET SOYUZ DOCKING MECHANISM

The Soviet Union is the only other nation to perform spacecraft dockings. The initial Soviet manned spacecraft docking took place in 1969 between two Soyuz spacecraft. In 1971, the first of many Soviet space station dockings occurred when Soyuz 10 docked with the Salyut 1 Space Station. The basic Soviet Soyuz docking mechanism is illustrated in Fig. 1.2. This is a probe-and-drogue design similar to the U.S. Apollo system, but the components pivot back into the spacecraft after docking in order to open a passageway.

APOLLO-SOYUZ TEST PROJECT

In 1972, the U.S. and the Soviet Union signed an agreement on cooperation in the exploration and use of outer space for peaceful purposes. This agreement led to the Apollo/Soyuz Test Project (ASTP), which culminated in July 1975 with the docking of a U.S. Apollo and Soviet Soyuz spacecraft. Since existing docking systems for both countries were not compatible, a compromise was reached involving a new docking system (Fig. 2). Rather than use a male/female probe-and-drogue design, the new ASTP docking system used androgynous interfaces (Fig. 3). The docking mechanism on each spacecraft had an identical ring-and-guide configuration interface which interleaved for docking. The mechanisms each had a 30.7-inch diameter central passageway for crew transfer. Two dockings were performed during the ASTP mission and the mechanisms performed flawlessly on each. The ASTP mission remains the sole international cooperative space mission involving docking of separate spacecraft.

The Soviets continued to use their probe-and-drogue mechanism to dock Soyuz spacecraft to their series of Salyut space stations. This system is still used today for the docking of Soyuz and Progress spacecraft to the new Mir Space Station. There has been no requirement for the U.S. to perform a docking since the ASTP mission. The Space Shuttle currently has no docking equipment, but with the advent of the Space Station, docking will be required of the Shuttle. At present, a number of Shuttle/Space Station docking hardware options are under review, including both Shuttle- and Space Station-mounted systems.

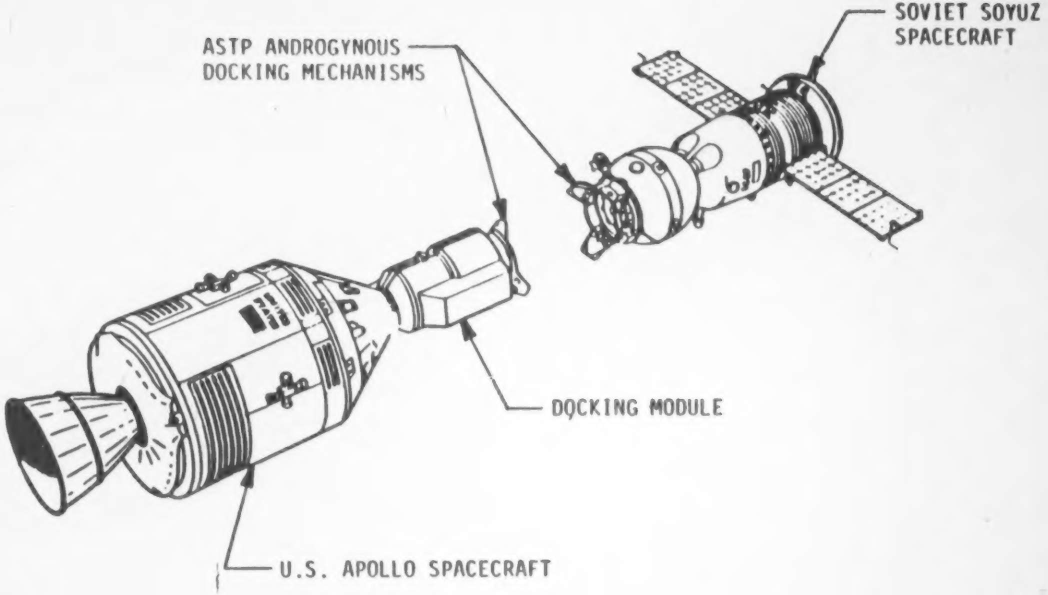
ASTP ANDROGYNOUS DOCKING MECHANISMS
SOVIET SOYUZ SPACECRAFT
DOCKING MODULE
U.S. APOLLO SPACECRAFT

FIGURE 2.0 APOLLO-SOYUZ TEST PROJECT (ASTP) SPACECRAFT DOCKING ARRANGEMENT

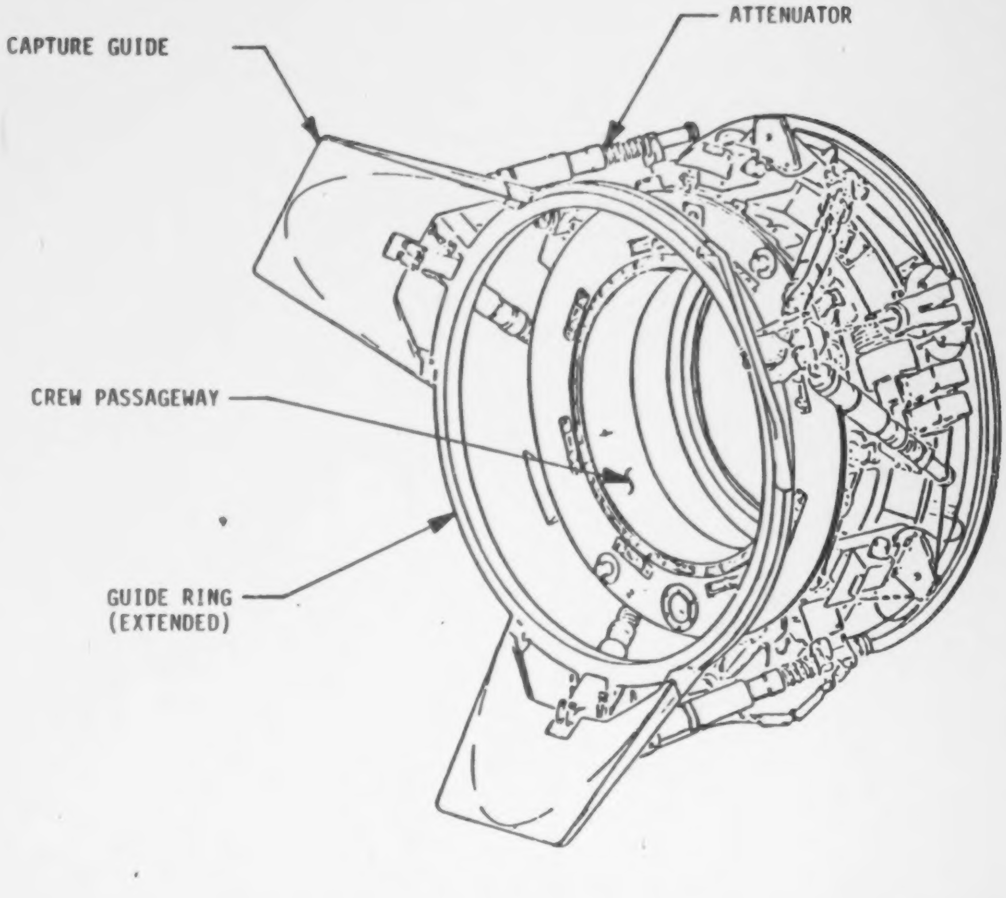
CAPTURE GUIDE
ATTENUATOR
CREW PASSAGEWAY
GUIDE RING
(EXTENDED)

FIGURE 3.0 APOLLO-SOYUZ TEST PROJECT (ASTP) ANDROGYNOUS DOCKING MECHANISM

A number of other nations, both singly and in partnership, are now planning manned space programs. Docking can be expected to be a key operational tool in many of these programs. The European Space Agency (ESA) has already begun discussions with the U.S. and the Soviet Union regarding the docking of its Hermes spaceplane to both the U.S. and Mir Space Stations.

DOCKING OPERATIONAL OVERVIEW

A spacecraft docking operation consists of four phases: rendezvous, approach, docking mechanism operation, and separation. The target spacecraft remains passive (i.e., non-translating) while the active chaser spacecraft performs all required maneuvers.

In the rendezvous phase, the chaser vehicle performs a series of navigation tracking and maneuvering segments to arrive at the approach initiation point at a desired time. The approach initiation point is usually considered to be approximately 1000 feet from the target spacecraft. Arrival time is based on desired orbital lighting conditions for the approach phase; the rendezvous trajectory/timeline is designed before mission.

Relative-state navigation capability is the most critical component of a rendezvous guidance, navigation, and control (GNC) system. The accuracy of relative-state determination has direct influence on safety, mission success, and fuel budget requirements. Ground-based tracking systems may be used to initialize the rendezvous. Onboard tracking systems are then utilized to support the rendezvous as it progresses. The target may provide active navigation aids such as radar transponders, tracking beacons, etc. Most targets however, do not provide such aids, and the rendezvous must rely entirely on an autonomous chaser navigational capability. In the future, the Global Positioning System (GPS) may be utilized extensively for rendezvous operations.

In the approach phase, the chaser vehicle approaches the target in order to bring the docking mechanisms into contact. Primary considerations are plume impingement, docking mechanism contact velocities and misalignments, and fuel usage.

Plume impingement is the term used for the impingement of rocket engine exhaust on a spacecraft. As the chaser vehicle approaches the target, it must fire its translation and attitude rocket engines (usually referred to as Reaction Control System, or RCS engines) to maintain alignment and the proper closing rate. The concerns here are with contamination of the target by the combustion products in the RCS engine exhaust plume and with forces and torques applied to the target as a result of the exhaust flow impinging on it. All spacecraft can be adversely affected by plume impingement and efforts at limitation must be made.

Docking mechanism contact velocities and misalignments, or contact conditions, determine to a great extent the size, weight, and complexity of the docking mechanisms. The contact conditions are driven by spacecraft controllability, stability, sensor accuracies, and pilot skill. The more slowly and accurately contact can be made, the smaller, lighter, simpler, and therefore, less costly, the docking mechanisms can be. Reducing contact velocities and misalignments usually requires more RCS engine firings though, leading to higher plume impingement and fuel usage. In the planning and execution of a docking approach, there will be a constant trade-off of these parameters.

Approach phase maneuvers can be performed manually, or they can be automated. For each method, appropriate short-range navigation and targeting sensors and aids are needed. As in the rendezvous phase, target "cooperation," that is, incorporating lights, specialized targets, or reflectors and transponders, can assure more accurate, reliable, and efficient approaches. It is also important that the target remain as stable as possible during the approach phase, giving the chaser a stable target for which to aim and helping to minimize last-second oscillations that can affect docking contact conditions.

Once contact is made, the docking mechanisms take over. The mechanisms on the two spacecraft must first be able to capture, align, and latch to each other over the expected range of misalignments. Next, they must arrest the relative motion of the spacecraft in a manner that limits resulting loads to acceptable levels. Finally, they must perform re-alignment, sealing, and any other functions as needed to fully establish a structural and pressurized connection between the spacecraft.

At the conclusion of the joint mission activities, the spacecraft must separate. The docking mechanisms are unlatched or otherwise disconnected; one or both spacecraft then fire RCS engines to move the spacecraft apart. Plume impingement is a concern here as in the approach phase. After a period of time, one or both spacecraft must make orbit change maneuvers to ensure that they do not make contact again. (NOTE: The post-rendezvous approach maneuvers and the pre-orbit change separation maneuvers are usually called proximity operations. This term will be used in the rest of the report to refer to both of these phases unless one or the other is specified.)

Docking is, by its very nature, a complex, multi-step operation involving many systems and mechanisms on both spacecraft as well as ground systems and perhaps satellites. An obvious but important point is that the least maneuverable spacecraft will generally set the requirements for mission planning and docking mechanism design.

Chapter 2: Potential Uses

This study did not attempt to project or define all of the potential specific missions; new, unforeseen uses for spacecraft and the space environment are continually being discovered. Availability of the capability to dock manned spacecraft of different nations could encourage development of new and innovative missions. A listing of overall categories of such missions follows:

MISSION CATEGORIES

o Personnel Rescue: Personnel rescue could involve the rescue of the crew of a disabled spacecraft, the removal of part of the crew of a space station which cannot sustain its normal crew complement for some reason (i.e., partial environmental control system or power system failure), or the return to earth or transfer between spacecraft of injured or ill crewpersons.

o Spacecraft Rescue: Spacecraft rescue could include the re-boost of spacecraft in critically decaying orbits or the performance of emergency repairs or maintenance by a second spacecraft and its crew to prevent loss of a disabled spacecraft.

o Scientific Experiments and Research: As demonstrated to some extent by the ASTP mission and in planning for the then proposed Shuttle-Salyut mission in the mid-1970's, nations could facilitate some types of experimentation and research.

o Direct Supply, Equipment, and Personnel Launch and Delivery: This would include the direct delivery from earth of both nominal and contingency articles and personnel. Nominal deliveries could include: scheduled consumables resupply; scheduled personnel transport and spacecraft element, equipment, and spare part delivery; and delivery of payloads and experiments. Contingency deliveries could include: non-scheduled or emergency delivery of consumables, medical supplies, spacecraft equipment or spare parts, and repair equipment; and transport of personnel with special medical or repair skills.

o Orbital Transfer of Supplies, Equipment, and Personnel: For nominal (scheduled) missions, this category is the same as the preceding, except that articles and personnel would be ferried between two spacecraft by a third one. For contingency (non-scheduled or emergency) missions, the articles and personnel may be ferried between two spacecraft.

o Return to Earth of Personnel or Equipment: Included would be scheduled or non-scheduled return to Earth of personnel or equipment. For personnel, this would typically involve the return at the end of a tour on a space station. For equipment, this may include return of failed, obsolete, or unused parts, payloads, or experiments.

o Commercial Ventures: Commercial manufacturing payloads have already flown on the Space Shuttle. A commercial man-tended space facility is also being planned for deployment in the 1990's. International commercial space missions could involve research, raw material delivery, processing and manufacturing, and product return to earth.

o Spacecraft Assembly/Construction: Cooperative missions could be used to assemble/construct earth-orbiting international space stations or international manned or unmanned spacecraft for earth-orbital, lunar, or Mars missions.

CANDIDATE SPACECRAFT/LABS

Although only the U.S. and the Soviet Union have actually flown manned spacecraft to date, several different nations, multi-nation organizations, and at least one private corporation are planning to build manned spacecraft. (There are actually two different types of "manned" spacecraft: continuously manned spacecraft such as the U.S. Shuttle, and man-tended spacecraft such as a space facility which could be visited routinely. Both types were considered in the study, and the term "manned spacecraft" will be used to refer to both collectively unless one or the other is specified.) A list of existing, planned, or officially proposed manned spacecraft may be found in the Appendix.

Although the scope of this study includes only manned spacecraft docking, it should be noted that unmanned spacecraft are also potential participants in international cooperative missions, as has been demonstrated by the Soviet Union in their MIR Space Station operations.

Of the manned spacecraft, only the following were considered for the design purposes of this study:

- U.S. Space Shuttle
- U.S. Space Station
- Commercially Developed Space Facility (CDSF)
- ESA Hermes Spaceplane
- ESA MTFF
- Soviet Soyuz Spacecraft
- Soviet Mir Space Station
- Soviet Heavy Space Shuttle

Focusing upon specific spacecraft was necessary to bound the analysis and focus the study. These craft were chosen because they are currently operational or are considered to have a high probability of being operational within the next decade. They are, therefore, the prime candidates for near-term cooperative missions. Brief descriptions, along with illustrations of each of these spacecraft, are included in the Appendix.

MISSION PRACTICALITY

In simple terms, such a feasibility, or practicality assessment, comes down to answering the following question: "Can two selected spacecraft dock, and if so, what activities can be performed?" The answer, combined with mission/spacecraft pair priorities, will serve to guide and bound mission planning and docking mechanism design negotiations.

Given the wide range of potential missions and spacecraft, it would not prove useful to perform a detailed practicality assessment of all possible mission/ spacecraft pair combinations. Instead, an effort is made to identify and define only the most important practicality factors to consider in initial cooperative mission negotiations and planning.

Identified practicality factors are discussed below in order of priority for crew rescue missions, with examples as applicable. The same factors though, in approximately the same order of importance, will apply to all potential cooperative missions.

Mission Practicality Factors

o Spacecraft Launch Considerations: Basically, this deals with the question of whether spacecraft launched from a given location can match orbit inclination and altitude with a selected orbiting spacecraft so that rendezvous operations are possible. First, with current U.S., Soviet, and ESA manned launch site latitudes (28.5° N, 46°N, and 5° N, respectively), and existing and projected near-term launch vehicle capabilities, ESA spacecraft can reach all U.S. and Soviet orbit inclinations, U.S. spacecraft can reach all Soviet orbits and ESA orbits inclined greater than 28.5°, while Soviet spacecraft can only reach U.S. and ESA orbits inclined greater than approximately 40°.

A closely-linked factor that must also be considered is spacecraft altitude capability. As orbital inclination (launch azimuth) increases, a given spacecraft's altitude and payload-to-orbit capabilities decrease. As a result, a spacecraft may not be able to reach the altitude of a selected spacecraft, or it may not be able to carry enough payload to a particular orbit inclination/altitude combination to make a given cooperative mission worthwhile.

o Orbital Maneuvering Capability: For some cooperative missions, especially rescues, it would be desirable to try to divert an already orbiting spacecraft to rendezvous with another. However, due to the large amounts of fuel needed for orbit altitude and inclination changes, this would only prove practical if the spacecraft are in approximately the same orbits initially. The U.S. Shuttle for example, in a 28.5° orbit with maximum possible OMS/RCS fuel, could only change its orbit inclination by approximately 2°, far short of that needed to rendezvous with a Soviet spacecraft such as Mir in a 52° orbit.

In all cases, the ability to divert orbiting spacecraft for cooperative missions comes down to fuel required compared with fuel available.

o Rendezvous and Proximity Operations Capability: The ability of two spacecraft to match orbits is meaningless for cooperative missions if they cannot then rendezvous and closely approach or dock. The main considerations and requirements for these operations are discussed in the Section on Docking Operations. It is important that special consideration be given to the disabled spacecraft. Closely approaching a disabled spacecraft for rescue may prove difficult or impossible if it is tumbling, or if necessary cooperative navigation or communication systems have failed.

o Response Time: The time available to complete a cooperative mission, particularly rescue or some scientific missions, may be very short. For non-space station-type spacecraft rescues, the time available may average only two to three days from the time an emergency is declared. (A Soviet Soyuz has a total on-orbit lifetime of only two days when not docked with Mir; the U.S. Shuttle has a nominal on-orbit lifetime of seven days and usually carries two to three days of reserve consumables.) It is very unlikely that currently available or near-term planned spacecraft could be readied and launched for an emergency mission within two to three days unless they were specifically on standby for a rescue or were already prepared for another mission. In the latter case, a timely rescue might still be very difficult to accomplish since time would be needed to remove payloads or other equipment, load rescue equipment and supplies, and load and verify new on-board computer programs.

Launch window considerations also enter into the calculations in this type of situation. Differing standard orbital inclinations and altitudes among the present and projected participants in manned spaceflight would lead to tight launch window constraints on missions intended to rendezvous and dock with spacecraft of another country. In addition, energy for changing orbits and supplies of consumables would further constrain the flexibility of such operations.

For space stations, the time available for rescue may be much longer; or, rescue missions may not be needed at all if the space station has its own return vehicles.

o Spacecraft Hatch Size: The types of activities that two spacecraft can engage in on cooperative missions will be determined to a large extent by their hatch sizes. The smaller hatch opening will define the size of articles such as supply containers, experimental equipment, or spacecraft parts that can be passed between the pressurized compartments of the spacecraft. Crew passage could also be restricted in some instances. For example, a person in a U.S. Space Shuttle spacesuit may find it difficult (depending on the clearances immediately behind and around the hatch opening) to pass through the 30.7 inch (0.78 m) diameter hatches used on Soyuz spacecraft and Mir.

o Personnel Accommodations: Cooperative missions involving transportation of personnel (for rescue or other missions) will be restricted by spacecraft personnel accommodations, i.e., life support system capabilities, consumables quantities, and physical size of pressurized compartments and/or the number of seats suitably stressed for launch and reentry loads. The most limiting spacecraft in this regard is the Soyuz; it has nominal accommodations for three persons and is probably not capable of carrying any more than that. The U.S. Shuttle could accommodate at least six or seven persons in an emergency in addition to a three-member flight crew. ESA's planned Hermes vehicle, with its three-person crew, has a very limited payload, and it is not clear how many persons it could accommodate in an emergency.

While it appears that many of these Mission Practicality Factors would render a discussion of international docking academic at best, it is also true that much of what may be impractical today in the area of docking could be overcome. As new spacecraft are developed, many of these factors could be specifically addressed.

To enable the maximum possible cooperation in space, all present and future manned spacecraft would have to be equipped with a standardized docking mechanism. However, given the wide disparity in spacecraft designs and potential differences in national or organizational space cooperation goals and requirements, an international agreement on a standardized docking mechanism would be required.

Were the United States to pursue a "universal docking" concept, the procedures agreed upon and used by the U.S. and Soviet Union in the ASTP Program would seem a reasonable (and proven) basis for developing the hardware and/or systems: establish a set of international docking interface standards and then enable each nation or organization to develop its own docking mechanisms that incorporate the international interface. With this approach, the ability to dock within certain performance standards is assured, but each nation or organization is free to tailor the design of its docking mechanism to fit its own individual spacecraft, spaceflight hardware design philosophies, and unique cooperative mission requirements. However, adherence to specific quality and design tolerances could be difficult to verify and would likely be a negotiating issue.

DESIGN REQUIREMENTS

When designing any mechanism, the first step is to fully understand the functions it must perform. Design requirements that define the key dimensions and functional performance standards must then be set. Only after this information is established can the mechanism, in this case a spacecraft docking mechanism, be designed.

In a manned spacecraft docking operation, the docking mechanisms on the two spacecraft must together perform the following basic functions, in sequence: capture one another; arrest relative spacecraft motion; structurally connect the spacecraft; establish a pressurized connection between the spacecraft; and finally, separate from each other when the mission is complete. These five functions can be considered as the system-level functional requirements for an international docking mechanism.

Sequential Docking Functions

Capture is the first function and involves the initial alignment and latching together of the two docking interfaces. Following the interface capture, the relative motion of the two spacecraft must be stopped. To safely achieve this, the docking mechanisms must be designed to balance stiffness and compliance so the relative motion can be arrested within a specified distance without overloading the docking mechanisms or the spacecraft structures.

After the relative motion has been stopped, a rigid structural connection between the spacecraft can be made. This connection must be capable of withstanding the pressure loads once the pressurized passageway is opened, combined with any other loads that may be applied to either spacecraft while they are docked.

A pressurized passageway of the desired cross-sectional shape and size between the two spacecraft must then be established. This can be complicated if the internal environmental pressure and/or composition is not compatible. The ATSP mission required an airlock (the Docking Module) in addition to docking mechanisms because of differences in Apollo and Soyuz atmospheres. The Docking Module restricted crew activities and weighed over 4,400 pounds.

When the mission is complete, the mechanisms must perform their last function, separation. Generally, this only involves disconnecting the structural connections and unlatching capture latches if they are still engaged; spacecraft RCS engines are then usually fired to fully separate the mechanisms and therefore the spacecraft.

Cabin Environmental Factors

Atmosphere composition and pressures would require standardization on candidate spacecraft, or at least the Environmental Control Systems (ECS) of candidate spacecraft should be capable of operating for short periods when exposed to the atmosphere of the docked spacecraft. This simplifies crew procedures and decreases both launch weights and costs.

All of the candidate spacecraft are known or believed to operate with similar oxygen/nitrogen, sea level pressure atmospheres. Also, several candidate spacecraft, notably the U.S. Shuttle, Mir, and Hermes, each incorporate internal airlocks at their docking port locations. Future candidate spacecraft designs could include integral airlocks, or be able to operate on cooperative missions as indicated above to avoid the procedural cost, and weight penalties of using special international docking airlocks.

For these reasons, it is logical to conclude that the only standardized hardware that should be required for international docking is the docking mechanism. Nations/organizations desiring to use, or whose spacecraft require the use of Docking (airlock) Modules, could provide their own unique equipment.

DOCKING MECHANISM DESIGN CONCEPTS

Design Approach

Conceptually, the advantages of an androgynous system are very clear. The number of candidate spacecraft is roughly doubled because any spacecraft having the docking mechanism can dock with any other spacecraft, not just those having the opposite kind of mechanism (i.e., probe vs. drogue). Also, only a single mechanism needs to be designed and developed.

The design of the Orbiter is such that, in order to save weight, the docking interface is, ideally, located deep in the payload bay. For this reason, a well-controlled mating is highly desired, i.e., berthing or using a docking mast. These two concepts are both being examined for the Orbiter to Space Station docking system. Such an approach will result in weight savings of 3,000 to 4,000 pounds for each Orbiter logistics flight to the Space Station. Imposing such a system on all candidate docking spacecraft would, however, greatly increase system complexity; it is also not truly androgynous. Consequently, a docking concept similar to that used for ASTP appears to be a reasonable alternative (i.e., each candidate spacecraft carries a hatch and a standardized androgynous mechanism.) The Space Station could also use this concept at an available port for visiting spacecraft. A module with a universal docking mechanism that can be extended above the Orbiter moldline could be developed for the Orbiter and flown as necessary.

RELEVANT CONSIDERATIONS

In addition to the rendezvous, proximity operations, and docking mechanism aspects of cooperative missions that have been discussed, there are several other items to consider with regard to spacecraft docking. Most of these items only indirectly affect the design of the docking mechanism, but they could have a significant impact on overall mission planning and development.

Attitude Control Systems Capabilities and Strategies: Once two docking spacecraft are latched together, they essentially form a single, new spacecraft. The attitude control system on one spacecraft, or the two spacecraft control systems working together, must be able to stabilize and perhaps maneuver this "new" spacecraft.

Equipment Mounting and Stowage: Finding room to mount or stow additional equipment (communications, guidance and navigation , and environmental control system), either permanently or only during cooperative missions, may prove to be difficult in some spacecraft.

Shadowing: When two spacecraft are docked, they will shadow one another; that is, partially or totally block the fields of view of solar arrays, radiators, antennas, optics, and windows. The critical effects of shadowing could be reduction of power generating capability, heating or cooling problems, and loss of communications.

Venting: Many spacecraft intentionally vent gasses and liquids while in orbit. When docked, such venting could pose a contamination problem to both the venting spacecraft and the second spacecraft.

Vehicle Tracking Aids: Some device(s) will be needed on the docking spacecraft to aid in determining their relative position and attitude.

Auto-Docking: Unmanned docking missions will need an auto-docking system; some manned missions may also need or benefit from the use of an auto-docking system. An appropriate sensor is critical to an auto-docking system. The sensor must be able to measure the relative spacecraft position, attitude, and rates, information that is required to successfully complete an unmanned auto-docking.

Chapter 4: Cost Estimate

Costs are an obvious and critical element in the assessment of any future option for the U.S. to develop a docking mechanism based upon international docking interface standards. The cost of designing and fabricating a particular mechanism would require significant resources, with the precise amount dependent upon the complexity of the device's design requirements.

The ASTP docking mechanism data is the most analogous historical information available to aid NASA in understanding the cost environment of a docking mechanism. In devising a cost estimate for this report, NASA utilized ASTP cost data, with appropriate adjustments for complexity, quantity and contractor expenses.

Were NASA to develop a docking system for the purpose of having a universal docking capability (based upon as yet unrealized international interface standards), the approach would be to build a docking system for the Space Shuttle, for the simple reason that the Shuttle is at present the only U.S. spacecraft that could utilize such a capability. Thus, estimating a cost to the U.S. for a universal docking system not only involves estimating the cost for a docking mechanism but also the cost for various Shuttle modifications. NASA's preliminary estimate for such an undertaking is on the order of $300 million in Fiscal Year 1988 dollars. This estimate provides but an order of magnitude. It is speculative and would remain so until more detailed design information is available.

Chapter 5: Concluding Observations

The results of NASA's study indicate that spacecraft docking equipment could be standardized, with a docking concept similar to that used for the Apollo-Soyuz Test Project identified as a reasonable alternative. That is, each candidate spacecraft could carry a hatch and a standardized androgynous mechanism. The developmental approach for the universal docking mechanism could be similar to that agreed upon and used by the U.S. and the Soviet Union. However, international docking agreements would be prerequisite to each nation's development of its own mechanisms to incorporate the universal interface. A critical issue for negotiation would be methods for enforcing adherence to quality and design standards by participating nations.

Potential uses would include assured return of spacecraft and space station crews, reboost of spacecraft, and various on-orbit repair scenarios. Opportunities may exist in other areas of international cooperation such as the earth-observing sciences, astronomy, transportation of raw and processed materials, and the like.

This is an era in which a growing number of space faring nations are conducting a growing number of space flights. It is a situation which implicitly offers increasing opportunity and potential for cooperation. However, if the United States decides to advocate such a program, it should be understood that the resources required for implementation will not be insignificant.

APPENDIX

CANDIDATE SPACECRAFT DESCRIPTIONS

APPENDIX: Candidate Spacecraft Descriptions

A.1 U.S. SPACE SHUTTLE

The U.S. Space Shuttle Orbiter is shown in Figure A-1. The Shuttle is approximately 122 feet long and has a wingspan of 78 feet. Maximum payload capability to orbit is 65,000 pounds; total spacecraft on-orbit weight is approximately 245,000 pounds. Payloads are carried in a 60 foot long, 15 foot diameter payload bay which forms the center of the fuselage.

Nominal crew size ranges from four to seven persons, but eight have been carried on one mission. EVA capability is provided on every mission. The crew cabin has a nominal 20% oxygen, 80% nitrogen, 14.7 psia atmosphere. A two-person airlock is contained within the crew cabin and opens out into the payload bay through a 40-inch diameter (maximum) D-shaped hatch.

The Shuttle does not have an integral docking mechanism, but does have full docking rendezvous and proximity operations capability. Docking mechanisms of appropriate design can be added to the Shuttle by installing them in the payload bay. Access to the crew cabin for docking must be through the payload bay airlock hatch.

A.2 U.S. SPACE STATION

The U.S. Space Station is planned to be a large, permanently manned, multinational space facility. The Space Station will be constructed in steps, leading to a basic operational configuration (Figure A-2.).

The core habitable elements of the Space Station are all interconnected. Nominal crew size for the completed Space Station will be eight. The habitable elements will use a nominal 20% oxygen, 80% nitrogen, 14.7 psia atmosphere. Currently, 50-inch square hatches (60.7 inch maximum diagonal dimension) will be used at all docking port and module/mode interconnection locations. The Space Station is not designed to perform rendezvous or proximity operations maneuvers.

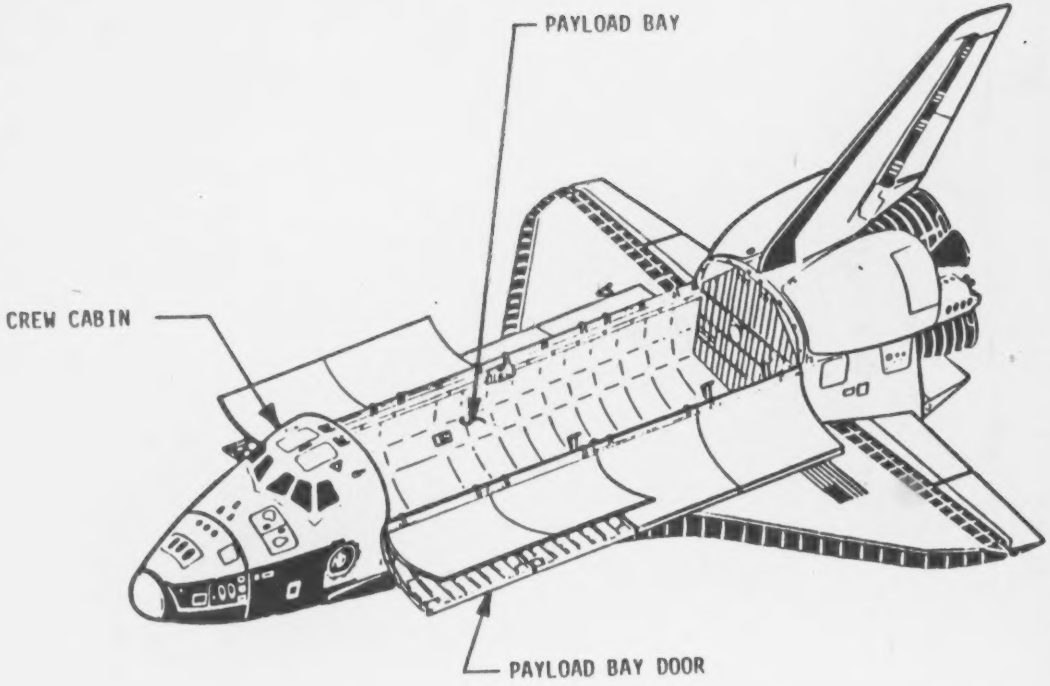
PAYLOAD BAY
CREW CABIN
PAYLOAD BAY DOOR

FIGURE A.1 U.S. SPACE SHUTTLE

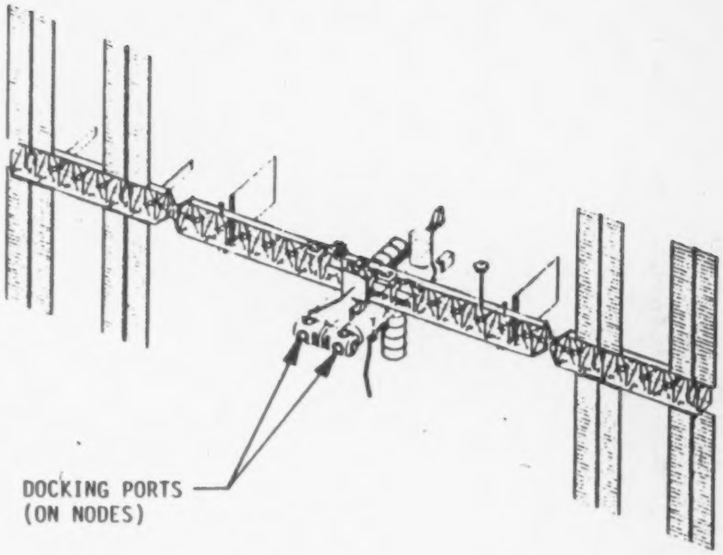
DOCKING PORTS
(ON NODES)

FIGURE A.2 U.S. SPACE STATION

The Space Station is planned to have two docking ports located side by side on the two forward nodes. Airlocks are not planned to be located at the docking ports. To date, Space Station docking studies have focused almost exclusively on requirements for U.S. Shuttle docking. A variety of hardware options are under consideration.

A.3 COMMERCIALLY DEVELOPED SPACE FACILITY (CDSF)

The CDSF is a proposed commercially developed space facility that operates in either a crew operated or free flying mode. The CDSF would be launched by either the U.S. Shuttle or an unmanned launch vehicle and supported solely by the U.S. Shuttle. It would be manned for periods up to 25 days during periodic shuttle visits. The CDSF would provide docking capability compatible with the docking mechanism of the Shuttle and elements of the Space Station. The details of the docking mechanism for the CDSF will be determined by the concept selected.

A.4 ESA HERMES SPACEPLANE

The ESA Hermes is shown in Figure A-3. It will be launched on an Ariane 5 Booster and will return to earth in a manner similar to the U.S. Shuttle. The current design is approximately 51 feet long with a wingspan of 34.8 feet. Maximum weight will be 44,000 pounds with a 6,600 pound payload. Nominal crew size is three. Hermes will use a nominal 20% oxygen, 80% nitrogen, 14.7 psia atmosphere. Current Hermes docking plans call for the use of a docking mechanism sized around the Space Station 50-inch square hatch located at the rear of the spacecraft. An airlock is located immediately forward of the docking mechanism, exiting through it.

A.5 ESA COLUMBUS MAN-TENDED FREE-FLYER

The ESA MTFF is an orbital man-tended facility planned to operate with and be supported by both the Hermes and the Space Station. The current design is

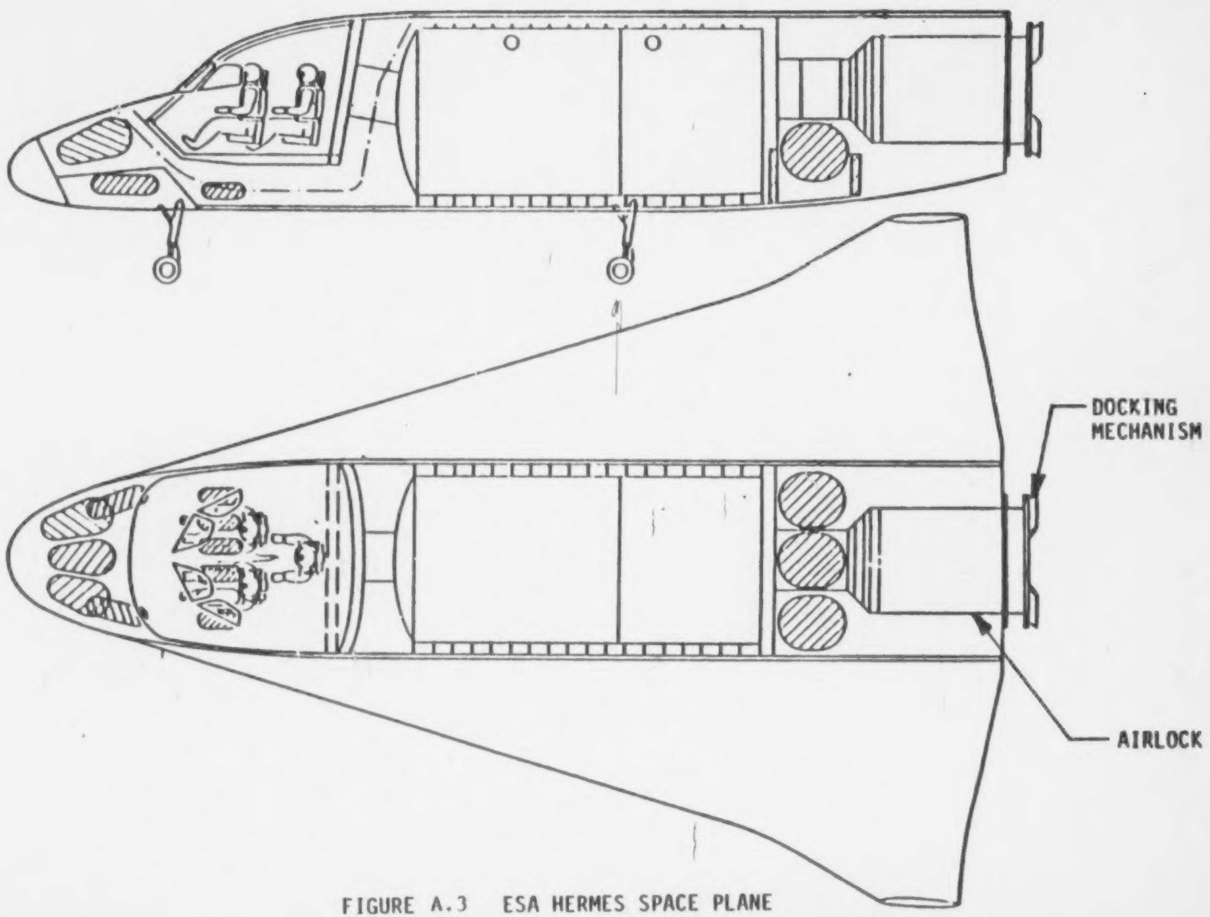
DOCKING
MECHANISM
AIRLOCK

FIGURE A.3 ESA HERMES SPACE PLANE

shown (with solar panels stowed) in Figure A-4. A 14.5 foot diameter by 23 foot long pressurized module forms the core of the MTFF. The internal atmosphere will be the same as the Space Station's. Total weight will be approximately 44,000 pounds.

A docking/berthing mechanism sized around the Space Station 50-inch square hatch is located at one end of the pressurized module. In order to mate with the Space Station, the MTFF will autonomously rendezvous with the Space Station and approach to a point where the Space Station manipulator can capture and berth it. For Hermes docking, it is assumed that Hermes will perform all of the maneuvers.

A.6 SOVIET SOYUZ SPACECRAFT

The Soviet Soyuz spacecraft (Figure A-5) is a non-reusable two person (some variants carry three persons) spacecraft that is currently used solely to transport crews to and from the Soviet Mir Space Station. The Soyuz is 22 feet long and has a maximum diameter (excluding solar panels and antennas) of 7.9 feet. Total on-orbit weight is estimated to be 15,000 pounds. The nominal Soyuz atmosphere is 20% oxygen, 80% nitrogen, 14.7 psia. A standard Soyuz probe-type docking mechanism is used, fitted to a 30.7 inch diameter circular hatch. When docking with the Soviet Space Stations, Soyuz performs all of the rendezvous and most or all of the approach maneuvers.

A.7 SOVIET MIR SPACE STATION

The Soviet Mir Space Station is a permanently manned space facility. The Mir core element, shown in Figure A-6, is approximately 43 feet long with a maximum diameter of 13.6 feet. Weight of the core element is approximately 44,000 pounds. The Mir is planned to be expanded through the addition of up to five separate modules, one of which is shown separate from Mir in Figure A-6. Mir is designed to operate with a 20% oxygen, 80% nitrogen, 14.7 psia atmosphere. Crew size is normally two. Mir has six Soyuz drogue-type docking ports - five are located on a docking module at one end of the core element while the sixth is located at the opposite end. Eventually, all but

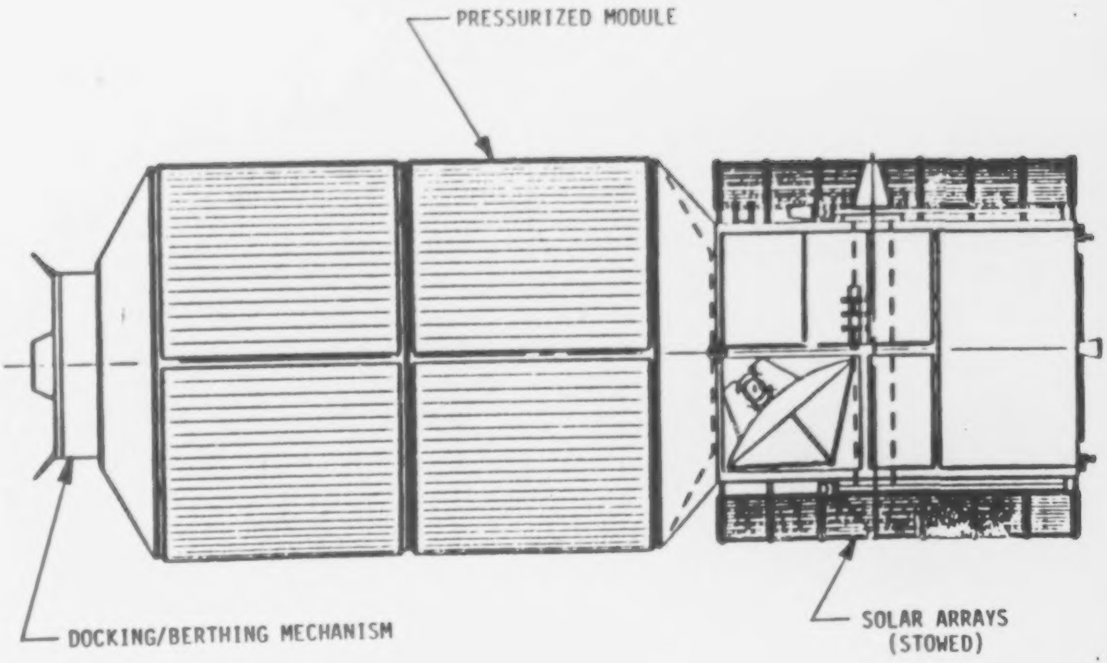
PRESSURIZED MODULE
DOCKING/BERTHING MECHANISM
SOLAR ARRAYS (STOWED)

FIGURE A.4 ESA COLUMBUS MAN-TENDED FREE-FLYER

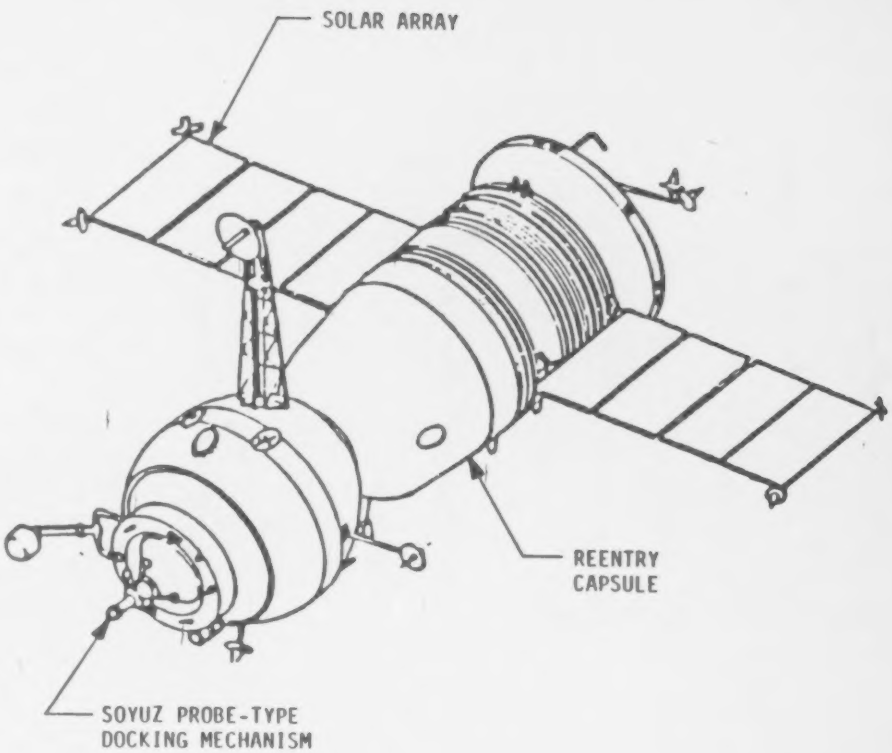
SOLAR ARRAY
REENTRY CAPSULE
SOYUZ PROBE-TYPE DOCKING MECHANISM

FIGURE A.5 SOVIET SOYUZ SPACECRAFT

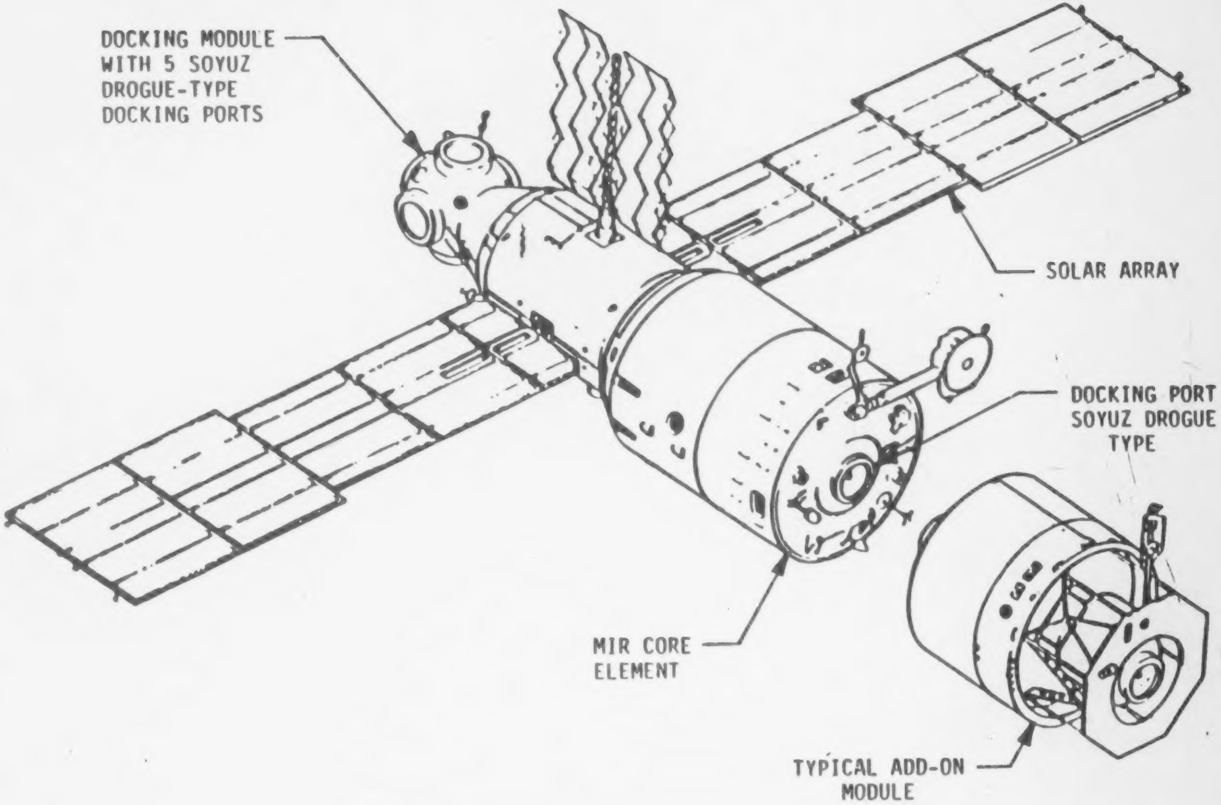
DOCKING MODULE WITH 5 SOYUZ DROGUE-TYPE DOCKING PORTS
SOLAR ARRAY
DOCKING PORT SOYUZ DROGUE TYPE
MIR CORE ELEMENT
TYPICAL ADD-ON MODULE

FIGURE A.6 SOVIET MIR SPACE STATION

the axial port on the docking module will be used for attachment of add-on modules. The axial port will remain free for Soyuz and Progress tanker/supply spacecraft dockings. Presently, Mir is capable of performing limited attitude change maneuvers to assist the Soyuz and Progress in their docking approaches.

A.8 SOVIET HEAVY SPACE SHUTTLE

The Soviet Heavy Space Shuttle is believed to be approximately the same size and have the same capabilities as the U.S. Shuttle. No illustration is available. Crew size, atmosphere composition and pressure, hatch sizes, and docking provisions are all unknown at present.

NASA
National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

APR 7 1988

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Pursuant to Section 107 of the Fiscal Year 1988 NASA Authorization Act, Public Law No. 100-147, I am submitting, herein, the Space Station Capital Development Plan for Fiscal Year 1989.

The plan contains an estimate of total costs for the Space Station Program, including projected requirements for funds outside of the NASA research and development account. It also contains an analysis of the Station's configuration and of the Space Station report conducted last year by the National Research Council, as required by Section 107(b) of the Act. In addition, the Capital Development Plan outlines a new program schedule. This schedule reflects the revised budget estimates for FY 1988 and FY 1989 and shows the first launch of a Space Station element to be early in 1995. The schedule presented in this report is an initial assessment, and it is our intent to revise the launch and assembly sequence to provide earlier man-tended laboratory capability.

We would be prepared to discuss this plan with you, if you wish.

Sincerely,

James C. Fletcher
Administrator

Enclosure

cc: Honorable Manuel Lujan, Jr.

NASA
National Aeronautics and
Space Administration

SPACE STATION
CAPITAL DEVELOPMENT PLAN
FISCAL YEAR 1989

Submitted to the

COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

and the
COMMITTEE ON COMMERCE, SCIENCE AND TRANSPORTATION
U.S. SENATE

Office of Space Station
National Aeronautics and Space Administration

APRIL 1988

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Capital Development Plan - FY 1989

Introduction

The "Capital Development Plan - FY 1989" is submitted in response to a directive from Congress found in the Fiscal Year 1988 NASA Authorization Act (P.L. 100-147). In accordance with Section 107 of the Act, the Capital Development Plan for Fiscal Year 1989 includes a statement outlining the projected total cost, schedule, and configuration of Space Station as well as an analysis of "The Report of the Committee on the Space Station of the National Research Council." The latter contains a discussion of the alternative configurations presented to the Committee. The Act requires the Capital Development Plan to be prepared for each of the fiscal years 1989 through 1996, and to be submitted along with the President's annual NASA budget request.

The President's National Space Policy affirms the national commitment to a permanently manned Space Station. The Space Station is essential if the United States is to maintain preeminence in key areas of civil space activities during the 1990's and beyond. The Station will stimulate the development of new technologies, advance scientific research, and help realize the commercial potential of space. Moreover, as a symbol of American technological prowess and competitive spirit, the Space Station directly supports our national goals in space. A permanently manned orbital complex is vital to America's leadership in human space flight.

The Space Station development program is making great strides toward fulfillment of the President's directive to develop a permanently manned Space Station within a decade. The configuration has been thoroughly reviewed, and the prime contractor teams chosen for Phase C/D, hardware development and advanced design. Key support contracts are in place and work has begun. A strategy to develop a Space Station Flight Telerobotic Servicer is also in place. An operations concept has been defined and baselined. User requirements are being factored into Space Station design. International negotiations with the European Space Agency, Japan and Canada are nearing completion. Thus, the Space Station has realized significant progress as it enters Phase C/D.

The Space Station Capital Development Plan for FY 1989

I. Total Space Station Development Costs

A. Introduction

A preliminary projection of the funding requirements by fiscal year from FY 1987 through FY 1993 for the Space Station Program is provided in Figure 1. Projected totals for the program are provided below. The fiscal year projections beyond FY 1989 are likely to be revised following completion of a program cost and schedule reassessment. This reassessment is being undertaken in accordance with the recommendations of the National Research Council's Committee on Space Station's report of September 10, I987. It is being accomplished with the full support and involvement of our Space Station contractors

The data presented in Figure 1 for FY 1988 are consistent with the Omnibus Continuing Resolution of Fiscal Year 1988. This resolution provides the Space Station Program with $325 million of FY 1988 New Obligational Authority (NOA), plus $100 million to be transferred from the Space Shuttle replacement Orbiter program. Of the $425 million provided for FY 1988, $225 million of NOA will be withheld from NASA until June 1, 1988. Additionally, for FY 1988, approximately $33 million has been transferred from the Research and Development account to the Research and Program Management account, in order to comply with requirements stated in the report accompanying the FY 1987 Housing and Urban Development--Independent Agencies Appropriations Act.

For FY 1990-1993, the preliminary estimates are stated in constant FY 1989 dollars, without provision for future year wage and price escalation. The estimates do not include provision for program scope beyond that presently approved.

Most of the funds for the Space Station Program are included in the Research and Development account: one of four accounts that together comprise the NASA budget. The other accounts are Space Flight, Control and Data Communications; Construction of Facilities; and Research and Program Management. The account structure is functional in character. It provides funding data for what NASA does. The agency conducts research, undertakes development, and operates spacecraft. The first two accounts cover these activities. The next two accounts are enabling in character. Construction of Facilities covers the building of buildings and is traditionally identified separately in budgets. Research and Program management covers the NASA institution, providing funds for personnel and associated administrative tasks in support of research, development and spacecraft operations. Underlying this account is the assumption that activities in space are an ongoing activity of the United States Government, not dependent upon any single space project.

B. Space Station

The budget line item within the Research and Development account for the Space Station program consists of: definition and technology development activities;

Figure 1
National Aeronautics and Space Administration
Preliminary FY 1989 Budget Estimates
CAPITAL DEVELOPMENT PLAN FOR SPACE STATION PROGRAM
in Millions of FY 1989 Dollars

	FY 87	FY 88	FY 89	FY 90	FY 91	FY 92	FY 93
RESEARCH AND DEVELOPMENT	420	399	987	2029	2612	2929	2664
SPACE STATION	420	392	967	2003	2565	2872	2593
Definition	250	0					
Design & Development	147	367	935	1936	2495	2793	2520
Flight Telerobotic Servicer	20	21	20	43	41	43	37
Transition Definition	0	4	12	24	29	36	36
Assured Crew Returned Capability (ACRC)	3	0					
SPACE TRANSPORTATION CAP DEV	0	7	20	26	47	57	71
SPACE FLIGHT, CONTROL AND DATA COMMUNICATIONS	3	5	11	33	74	90	118
SPACE TRANSPORTATION OPERATIONS					0	6	40
SPACE & GROUND NETWORK, COMMUNICATIONS & DATA SYSTEMS	3	5	11	33	74	84	78
CONSTRUCTION OF FACILITIES	17	2	30	91	25	43	4
RESEARCH AND PROGRAM MANAGEMENT	80	95	98	101	104	107	110
TOTAL SPACE STATION	$520	$501	$1,126	$2,254	$2,815	$3,169	$2,896
(Non-Add Space Station Operations)				($24)	($72)	($171)	($447)

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design and development of the baseline Space Station; the Flight Telerobotic Servicer's definition, design and development; "transition definition"; operations; and, for FY 1987 only, the concept definition studies for a Crew Emergency Return Vehicle.

In testimony before the Congress last year, NASA presented its cost estimate for the design and development of the Revised Baseline Program, based on a First Element Launch in March 1994. This estimate was 12.2 billion in 1984 dollars, which is equivalent to 14.6 billion in 1988 dollars and 15.3 billion in 1989 dollars. This estimate of the design and development costs has not been revised for this Capital Development Plan, because the estimate is under review. However, the stretchout of the development schedule due to reductions taken in the previously planned funding through FY 1989 will require sustaining base support over a longer period. This is likely to raise the total cost of the Space Station.

Development costs refer to those funds required for the design, fabrication and testing of the Station itself. Development costs do not include those costs to be incurred for Station operations, payload/experiments or transportation to and from the Station.

In other research and development accounts of the Space Station are the program's Flight Telerobotic Servicer (through 1993, $225 million), "transition definition" ($141 million through 1993) which is the planning necessary to evolve smoothly from Space Station development/assembly to steady-state operations, and a Crew Emergency Return Vehicle (CERV) study ($3 million). In addition, the FY 1987 funds utilized by NASA to define the Space Station concept ($250 million) are separately identified. Definition funding concluded in Fiscal Year 1987. NASA believes the funds so utilized constituted a sound investment, contributing significantly to the strong design of the Space Station. With these funds, the total research and development cost of the Station is $12.0 billion through 1993. This estimate does not include the program stretchout cost. Further, the revised estimates expected later this year will reflect contractor inputs as well as private sector initiatives. Since this is a capital development plan, the preliminary funding requirements for Space Station operations are shown parenthetically for information only.

C. Space Transportation Capability Development

The Space Transportation Capability Development line in the Research and Development account in Figure 1 amounts to $228 million provides for assessments by NASA through the Office of Space Flight of possible Station transportation options and the development of new and improved capabilities needed for Station assembly and operations. These capabilities include the Space Shuttle-Station docking system, the upgrade to the Shuttle's remote manipulator system, and Space Station crew transportation. Follow-on study funds planned for FY 1988-1990 for CERV are also found in this Space Transportation line. Estimated funding necessary to design, fabricate and test such a transportation vehicle are not included. No decision on whether a vehicle is required or, if so, what kind of vehicle it should be, has been made. Also not included in this section of the Research and Development account are the estimated funding requirements for transporting the Station elements into orbit and assembling them. These estimates are found in "Space Transportation Operations," a separate section which is discussed next.

D. Space Transportation Operations

Estimated Space Shuttle transportation costs through FY 1996 for Station launch and assembly are displayed in the Space Transportation Operations section of the Space Flight, Control and Data Communications account. The assembly phase of the manned base of the Space Station will require 19 Space Shuttle flights. Of these 19 flights, 13 are to carry aloft and assemble Station elements. Four flights are for logistics. Two flights are for outfitting the laboratory and habitation modules. The U.S. polar platform could be launched by a Titan IV class unmanned launch vehicle. The overall transportation costs are estimated to be $740 million through FY 1996, based upon a marginal cost per flight of $46 million (FY 1989 dollars). The estimate also includes the potential use of a Titan IV, priced at $148 million (in 1989 dollars). (The total transportation cost through assembly completion in FY 1998 is $1,022 million.) The European Space Agency is expected to launch its polar platform with an Ariane booster. The cost estimate depicted here is associated only with the 20 U.S. launches. Potential offsets to direct funding requirements through the receipt of reimbursements for the Shuttle launch of the ESA and Japanese modules have not been incorporated into these estimates. As indicated, the Shuttle cost per flight is calculated using a marginal cost estimating approach.

It should be noted that the President's budget request for FY 1989 includes funds to develop an Advanced Solid Rocket Motor (ASRM) for the Space Shuttle. These funds are not shown in Figure 1, as they are not associated with the Space Station Program. Performance increases to the Shuttle from the ASRM could affect transportation to the Space Station, however. Greater mass per flight could be carried aloft. Margins could be increased, and the number of Shuttle fights required for Station assembly could be reduced from 19 to 14, based on recently completed analyses. Were the latter to occur, the total for transportation costs would be reduced accordingly.

E. Space and Ground Network, Communications and Data Systems

Operation of the Space Station will require considerable tracking and data acquisition capabilities. One of the significant technical advancements of the Space Station comes in the field of data generation and management. These capabilities are the responsibility of the NASA Office of Space Operations. Funding requirements are shown in the Space and Ground Network, Communications and Data Systems section of the Space Flight, Control and Data Communications account. The funds will be used for the Space Station elements of the Customer Data Operations System (CDOS), which will provide data capture, processing, and polar platform control capabilities for the Space Station. CDOS will also provide tracking, data acquisition and communications, the latter through the Tracking and Data Relay Satellite (TDRS) system. Through FY 1993, the estimated funding requirement is $288 million.

F. Construction of Facilities

Many NASA flight projects require new, unique, or modified facilities for their development and/or operation. The Space Station is no exception, although the facilities requirement for the Space Station Program is relatively modest for a program of its size and duration. NASA will use many existing facilities for the Space Station endeavor. The estimated funding currently projected for new or modifications to the existing physical plant total $212 million through FY 1993 is in constant FY 1989 dollars. Areas where new buildings are required for the Space

Station activity include pre-launch processing, logistics, training and simulations, and human performance tests.

G. Research and Program Management

The NASA R&PM line consists of the direct salaries and benefits for civil servant personnel that support the Space Station program. The overall staffing requirements for the Space Station are currently under review. The estimates in Table 1 do not provide for increasing the level of personnel above the FY 1988 level. Through FY 1993, the total cost for R&PM is $695 million.

II. Overall Space Station Program Schedule and Program Milestones

The Space Station schedule includes programmatic and internal management milestones. Programmatic milestones reflect the time periods during which major technical events important to the program should take place. Management milestones focus primarily on cost and budget reviews as well as top-level program reviews and other management oversight activities. Establishment and completion of both kinds of milestones are essential to the successful development and operation of the Space Station.

The Space Station schedule, like any other, reflects the available funding projections. The budget reductions, necessitated by the Bipartisan Summit Agreement, caused a slip in the schedule as system development is stretched out to reduce near term outlays. The schedule indicated in Figures 2 and 2A is consistent with the budget provided in the FY 1988 Omnibus Continuing Resolution, and reflects the adjustments necessitated by the Congressional reductions to the FY 1988 budget request for the Space Station and the President's FY 1989 budget.

Preliminary assessment of the impact of the budget reduction resulted in a planned slip in the programmatic schedule of approximately one year for key milestones. If a decision is made to delay some parts of the program while holding others at their original dates, the schedule will again change. NASA is examining whether it is fiscally or technically possible to maintain the schedule for development of those systems necessary for a man-tended capability, while extending the schedule for the rest of the systems needed for permanently manned capability. Although limited in capability, the Station in a man-tended phase will enable certain kinds of early research to be done.

The impact of the FY 1988 budget reduction is still being examined by the NASA centers and major contractors; thus, the milestones dates, independent of policy decisions, may change. Also, with a Shuttle equipped with an Advanced Solid Rocket Motor (ASRM) for assembly, the schedule slip might be shortened because less flights would be needed to assemble the Station.

Two of three key programmatic milestones will be delayed, although somewhat less than the hardware launch dates. The Program Requirements Review (PRR), scheduled to begin in April 1988, will remain on schedule and will be completed in July. The Preliminary Design Review (PDR) and the Critical Design Review (CDR) will slip six to nine months. All three of these reviews are critical to a well-designed, integrated Space Station. PRR will verify the requirements for the program and enable the detailed design and development process to begin. The PRR process will assure complete and consistent specification of the program, and the achievability of the requirements within the available technical and fiscal resources. The PDR, scheduled to occur in mid-1989, will then provide an early review and assessment of the Space Station system design, of Station elements, system, subsystem, and lower level designs to assure that the overall design satisfies requirements. The CDR will be a final critical review of the detailed design and test plans of all ground and flight aspects of the Space Station program. CDR will begin in mid-1991.

The preliminary revised Space Station schedule establishes the First Element Launch (FEL) in early calendar year 1995, man-tended capability in the last quarter of calendar year 1995, and a permanently manned capability in the last quarter of 1996. Launch of the polar platform is still scheduled for late 1995.

Figure 2
SPACE STATION
PROGRAM MILESTONES

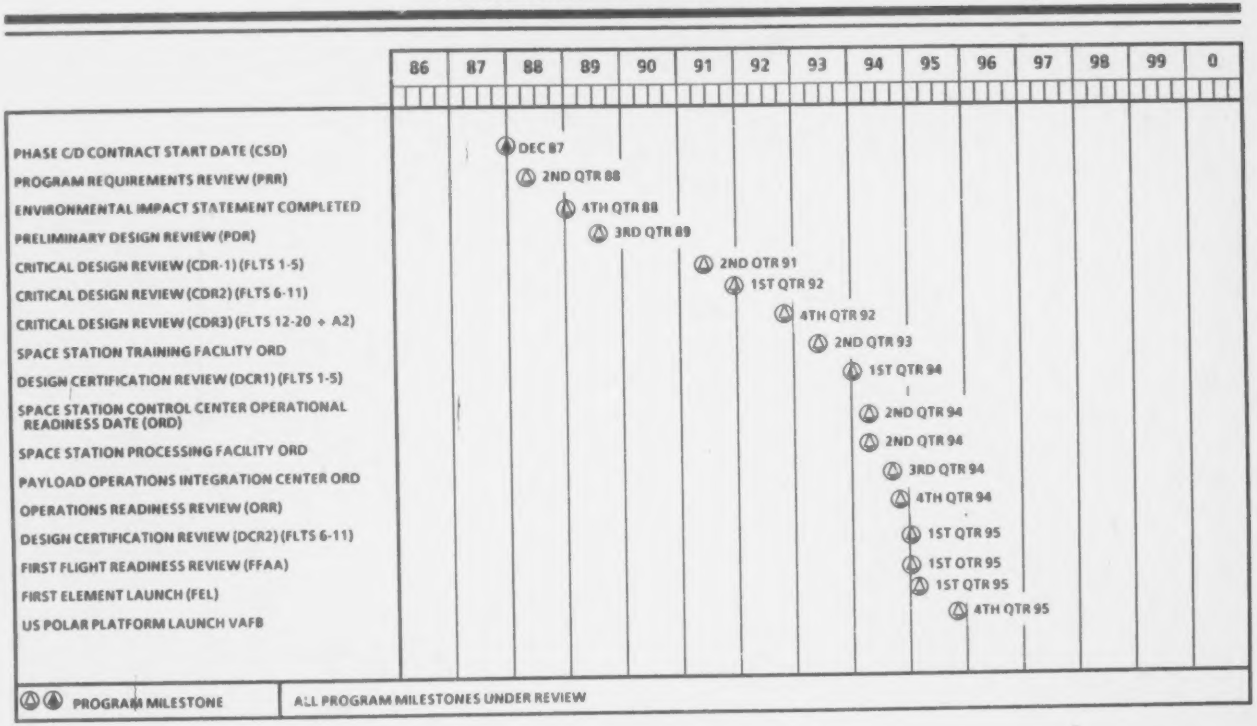

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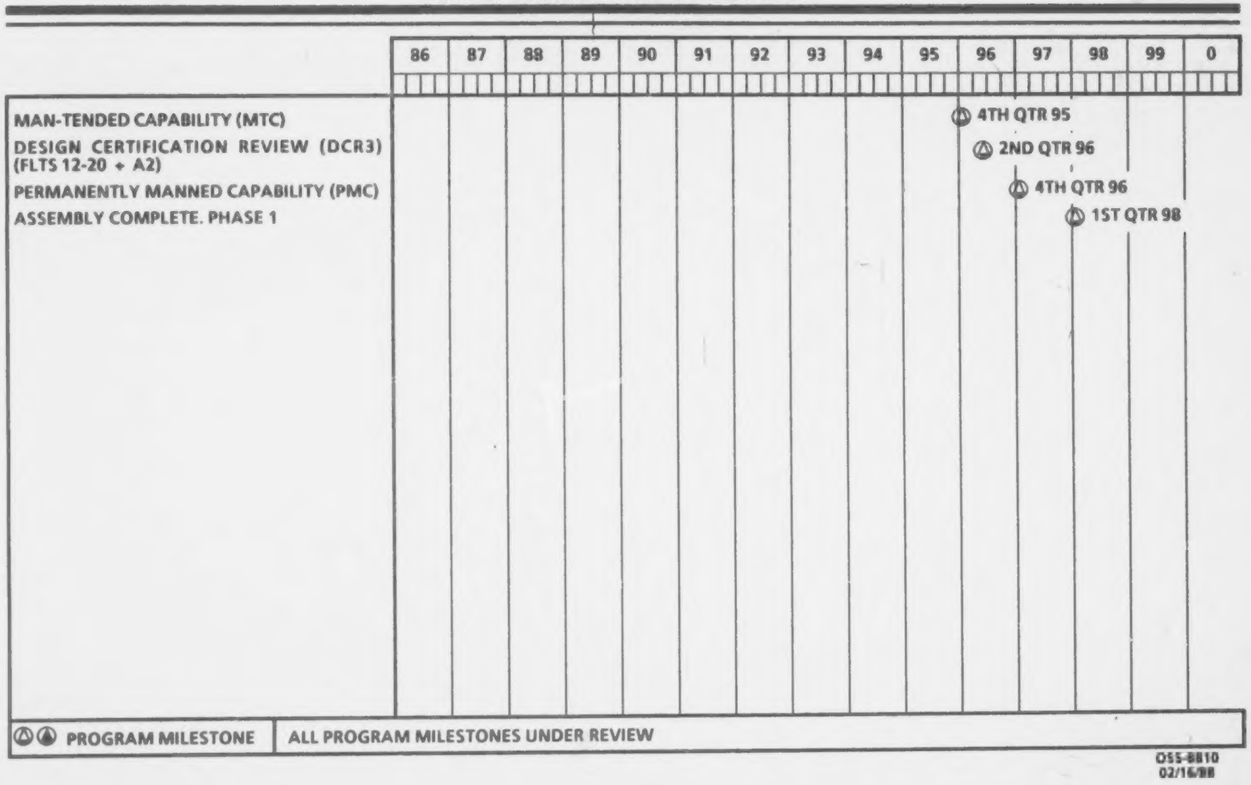
Figure 2-A
SPACE STATION
PROGRAM MILESTONES



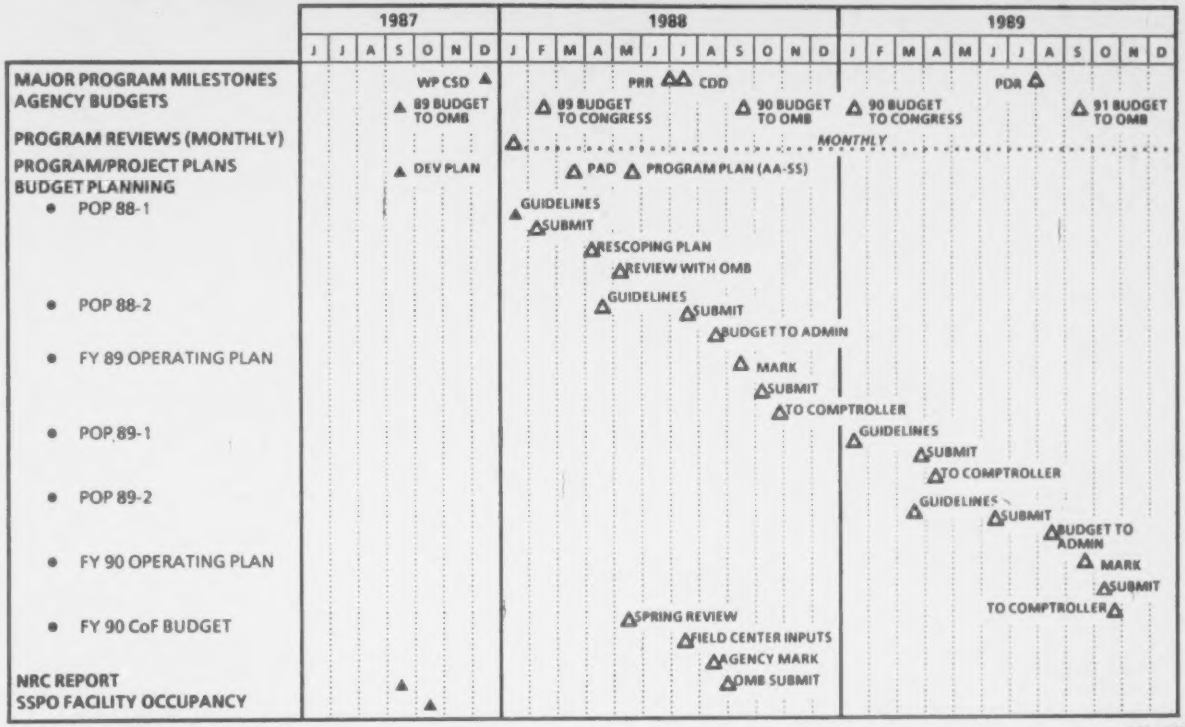
Internal management milestones, Figure 3, are key to the control of the program. NASA realizes that cost control is absolutely central to management of the program, and is determined to track costs very closely. Cost control for the Space Station program is accomplished through a standard NASA system of project or program operating plans (POP). These operating plans are the framework for a detailed assessment of costs at all levels of the program. The POPs are part of an ongoing process which provides guidelines to the work package centers, who in turn submit their requests for funding. These requests go through extensive and detailed review at Level III (including by Center Directors), at Level II in Reston, at Level I at NASA Headquarters, at the NASA Comptroller's Office, and at the Office of Management and Budget. Further, NASA is establishing effective cost control mechanisms for both development and operations in order to manage the program within total cost allocations. In this manner, costs are controlled, the NASA budget is implemented, and operating plans consistent with the budget are established. Program progress against the plan is reviewed monthly to assess planned versus actual costs. The program is adjusted within funding constraints semi-annually as necessary.

In addition to the regular POP schedule, thorough "bottoms-up" cost reviews are undertaken on an as needed basis. An internal review of this nature was held in late 1986. Should there be a large, unexplained contractor overrun, or unforeseen technical difficulties, further special programmatic cost reviews for the Space Station would be held. Internal cost reviews are supplemented by external assessments.

Other critical budget and management activities include program reviews, budget and resource requirement updates, internal (NASA) and external (OMB, Congress) budget updates, and Construction of Facilities status reviews. Table 3 depicts these milestones for FY 1988 and 1989.

NASA will continue to exert considerable control over the cost and schedule of the Space Station. While it is too early to tell how much impact the budget reductions have had on the schedule, every effort will be made to see that the impact is minimized as much as possible. NASA intends to develop the Space Station in a timely and controlled manner that realistically takes into account both technical and fiscal constraints.

Figure 3
SPACE STATION
INTERNAL BUDGET REVIEW MILESTONES



CDD - CONTRACT DEFINITIZATION DATE
CSD - CONTRACT START DATE

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III. The Baseline Configuration

The baseline configuration description outlined below is intended to provide an understanding of the Space Station design approach, a physical description of what the Station will look like, and an idea of how it will function. The description focuses on the hardware and distributed systems that will make up the Station, with primary emphasis on the U.S. areas of responsibility.

A. General Description

The Space Station Baseline configuration evolved from an extensive analysis of scientific and commercial user requirements, as well as transportation considerations, and engineering and technology factors. The Phase B preliminary design, completed in January, 1987 after 21 months of extensive analysis by both NASA and industry, firmly established an architectural concept for the Space Station configuration. During Phase B, a Critical Evaluation Task Force (CETF) reviewed and validated the Baseline configuration design--the Dual Keel. The Dual Keel was subsequently scaled down to the present Baseline configuration described here after costs were reviewed. The CETF also developed options concerning the assembly process, safety, transportation capability, operations and early productivity. Also, an Operations Task Force established operational concepts to be used in Space Station design.

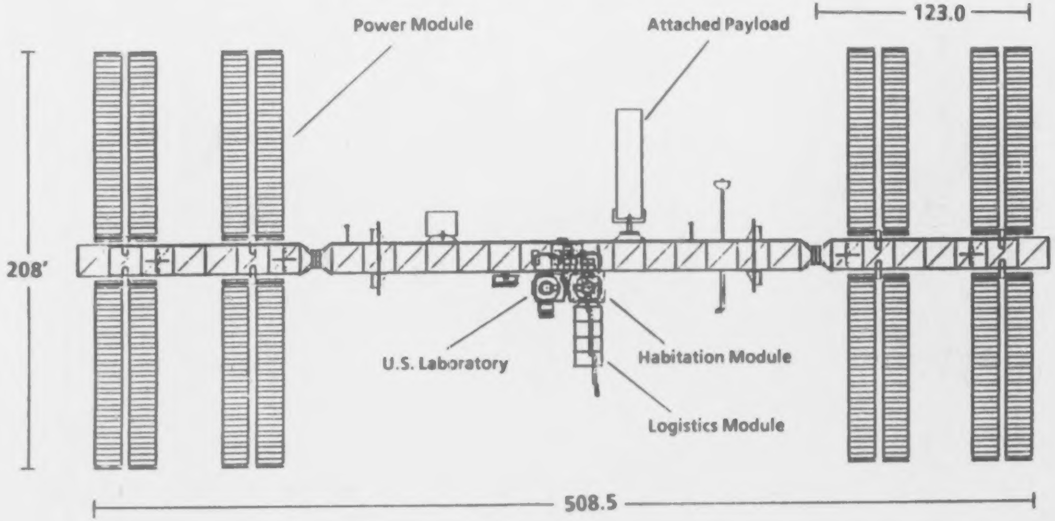
Although the Phase B revised architecture configuration will be used as a baseline for design and development during Phase C/D, the design will mature as the Preliminary Requirements Review (PRR), Preliminary Design Review (PDR) and the Critical Design Review (CDR) are carried out. Therefore, the considerable detail described in this report is subject to change as Phase C/D proceeds.

The Baseline configuration includes a manned core Station and two associated unmanned platforms. These will be polar orbiting platforms, one developed by the United States and one by the European Space Agency (ESA). In addition, ESA will develop a Man-Tended Free-Flyer.

Space Station elements will be held together by attachment to a 262.5 foot (80 meter) long transverse boom flying perpendicular to the velocity vector (see Figure 4). It will be designed to operate from approximately 150 nautical miles (276 km) to 270 nmi (500 km) at a 28.5 degree inclination. The nominal operating altitude will be approximately 220 to 250 nmi. Four pressurized cylindrical modules will be located in the center of the Station. The Habitation module will provide living quarters for up to a crew of eight. The United States, ESA, and Japan will each develop a laboratory module. Also, pressurized and unpressurized logistics carriers will provide supplies and equipment. Finally, there will be limited provisions for payload servicing.

The Station will be powered by two power modules, each composed of two pairs of photovoltaic arrays. The T-shaped 123 foot (37.5 meters) long power modules will be attached to either end of the boom with two alpha joints, which will rotate to point the solar arrays toward the sun. With the power modules, the total length of the Station will be 508.5 feet (155 meters). The power modules will supply an average total of 75 kilowatts (kW) of electrical power. The boom will be equipped with attach points providing power and other utilities to accommodate a variety of external scientific payloads.

Figure 4
BASELINE CONFIGURATION - FORWARD VIEW


123.0
Power Module
Attached Payload
208'
U.S. Laboratory
Habitation Module
Logistics Module
508.5

OSS-8490
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Other features of the Space Station will include a Canadian Mobile Servicing System. This system will be used to assist in the assembly of the Station and for a number of servicing tasks. There will also be a Flight Telerobotic Servicer, which will be used to service payloads and which will also be used in the assembly of the Station.

Space Station elements are the major pieces of hardware that are assembled to make up the Space Station. Elements comprise the hardware of the Station that is not involved with distributing a utility or service. Distributed systems, in contrast, provide those functions whose end-to-end performance is located in two or more elements. The Station will have a number of distributed subsystems which will provide data management, thermal control, communications and tracking, guidance, navigation and control, environmental control, human life support and fluid management. A more comprehensive functional and physical description of Space Station elements and distributed systems follows.

B. Space Station Elements

1. Transverse Boom

The boom will be a 262.5 foot long truss assembly that will give structural stiffness and dimensional stability to the entire Space Station. The truss will also provide the structure for integration and installation of all the elements and systems, including the modules, that make up the Space Station.

The core truss will be a framelike structure made up of longerons, battens, and diagonal struts designed to be assembled in space. These members, made of composite materials, will be attached to corner fittings forming a beam truss of sequential cubic bays measuring five meters wide from strut centerline to strut centerline.

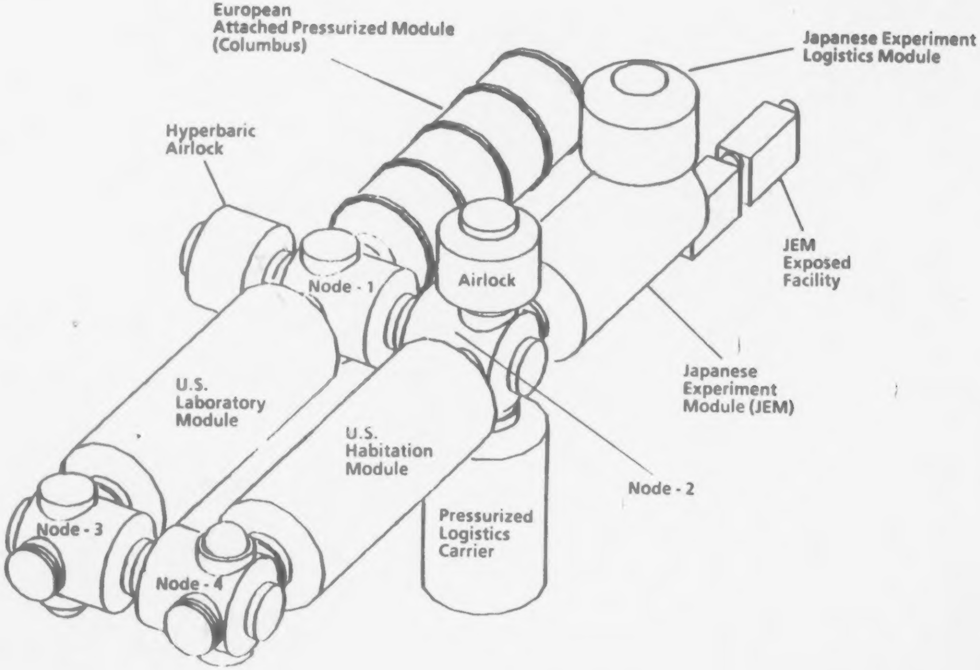
The overall truss assembly will include the core truss structure, EVA (extravehicular activity) truss equipment to facilitate crew movement about the Station, an external lighting system, utility distribution trays, resource pallets, and an alpha joint and drive mechanism used to turn the photovoltaic power modules. Utility distribution trays will house all the subsystem distribution lines--thermal, power, fluid and data management--for the Station. Utility ports, equipped with common interfacing hardware, will be provided for external attached payloads.

2. U.S. Laboratory Module

The U.S. laboratory module will be used to conduct basic microgravity materials and life science research. The experiments conducted there will be those which require low gravity levels over long periods of time, and extensive human control and monitoring. The commercial potential of materials processes in microgravity will also be investigated in the U.S. laboratory module (see Figure 5).

The U.S. laboratory module will be located below the lower face of the transverse boom. It will be attached perpendicular to, and slightly to the right of center, on the boom. The laboratory will be a pressurized cylinder, 14 feet in diameter and approximately 44 feet in length. The ports at either end of the module will be 7 feet in diameter. It, like all the major components of the Space Station, will be designed to fit in the Space Shuttle cargo bay. The ends of the module will attach to Nodes 1 and 3.

Figure 5
PRESSURIZED MODULE CONFIGURATION


European
Attached Pressurized Module
(Columbus)
Japanese Experiment
Logistics Module
Hyperbaric
Airlock
JEM
Exposed
Facility
Node - 1
Airlock
Japanese
Experiment
Module (JEM)
U.S.
Laboratory
Module
U.S.
Habitation
Module
Node - 2
Pressurized
Logistics
Carrier
Node - 3
Node - 4

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The module structure will be composed of two basic structures and a number of layers. The primary structure will consist of a pressure shell, meteoroid shield, and radiation protection. It will also have Space Shuttle attachment provisions, viewports, and grapple fixtures. The secondary structure will be an inner wall that provides rigidity for attaching experiment racks and other equipment. Utility lines will also be mounted to this structure.

The interior of the laboratory module will be pressurized at 14.7 psi (sea level pressure), and will be able to accommodate up to 42 cubic meters (30 double racks) of payloads and payload support equipment. These payloads and related equipment will be located along the port and starboard walls of the laboratory. The Environmental Control and Life Support System (ECLSS), other distributed system components, laboratory outfitting equipment,and storage lockers will be placed along the floor and ceiling.

3. Habitation Module

The habitation module will be the living quarters for the crew. It will be designed to include safe haven emergency supplies and provisions to allow its isolation from the other modules. The habitation module will be where the crew eats, sleeps, engages in recreational activities, and receives medical care when necessary.

The habitation module will be identical in size and structure to the U.S. laboratory module and will be located parallel and next to it. Like the laboratory, the habitation module will have both a primary and secondary structure. The interior will be outfitted with the means for cooking, eating, personal hygiene, and other human needs. Exact outfitting equipment has not yet been specified. The floor and ceiling will contain stowage areas for spares, consumables, tools for subsystem maintenance, and troubleshooting equipment.

4. European Attached Pressurized Laboratory Module

The European module will be a permanently attached, pressurized laboratory module developed and funded by ESA. The module, 41 feet in length and 14 feet in diameter, will be composed of four segments of all-welded primary structure with axially mounted Station-compatible docking ports at each end. The internal secondary structure will include removable single and double racks for accommodation of subsystems and payloads. The module will also contain a scientific airlock to permit temporary exposure of experiments to a vacuum. The airlock will also be used to transfer tools and equipment to support external activities.

5. Japanese Experiment Module (JEM) and Exposed Facility

Japan will provide the JEM, consisting of a permanently attached, pressurized laboratory module, an exposed facility, and an Experiment Logistics Module (ELM). The pressurized module will be 35 feet long and 14 feet in diameter. The exposed facility will be 25 feet long. The pressurized portion of the JEM will have a structure similar to the U.S. modules. The exposed facility will consist of an open truss and equipment-attach provisions. An airlock will provide access between the pressurized module and the exposed facility. The ELM will provide transportation and storage of supplies, and potentially could serve as a safe haven for two crew members.

6. Resource Nodes

The Space Station will have four resource nodes, located at each end of the habitation and U.S. laboratory modules. The nodes will be small pressurized cylinders that will generally serve as command and control centers, and as pressurized passageways to and from the various modules. The nodes will provide additional pressurized space for the Space Station. They were added to the preliminary design to accommodate early astronaut concerns about the amount of extravehicular activity (EVA) that would be required to assemble the Space Station . By housing a number of Station systems inside the nodes, EVA time was reduced.

The nodes will be pressurized cylinders approximately 14 feet in diameter and 17 feet long. They will be developed like the modules, with a primary and secondary structure and containing accommodations for distributed systems. Certain nodes will also contain berthing mechanisms for temporary attachment of either the Space Shuttle or the logistics modules. They will also have attaching elements to connect the node to the truss and modules. One or more cupolas may be attached to node ports to allow direct viewing of external activities. The nodes will also contain docking equipment and hatches.

As the Station is presently configured, Node 1 will be the unmanned spacecraft control center, controlling both unmanned flights and man-tended operations. It will be located between the Columbus and U.S. Laboratory Modules, and will attach to the hyperbaric airlock (explained later) and Node 2. Like Node 2, it will contain a berthing mechanism to allow the temporary attachment of the logistics module. Node 1 likely will also contain major components of the propulsion subsystem.

Node 2 may be the man-tended command and control station. It will also probably contain the airlock control station and the berthing elements for the airlock. It will be located between the Japanese Experiment Module (JEM) and the U.S. Habitation module.

Node 3 will likely be the primary command and control station for the pressurized areas of the Space Station. It will be located at the forward end of the U.S. Lab module, and will contain berthing mechanisms for the Space Shuttle. This node could also contain such equipment as the control mechanisms for the distributed utility systems, mechanisms for module-to-node interfacing, a control station for proximity operations, a port for pressurized attached payload accommodations equipment, and a backup control station for the Mobile Servicing System (MSS). It will also contain the necessary scars (hardware provisions) for future module pattern growth.

Node 4 could potentially be the proximity operations station, and prime MSS control station. Attached to the forward end of the U.S. Habitation module, and connected to Node 3, it will provide a pressurized passageway to and from the modules. It will contain the NSTS berthing mechanism, and mechanisms for cupola attachment for the proximity operations control station. Like Node 3, Node 4 is scarred for growth.

7. Logistics Carrier

There will be two types of Space Station logistics carriers: pressurized and unpressurized. Both will be used to transport equipment and fluids to the Space Station and to return experiment results, equipment, and waste products back to

Earth. They will be carried in the Orbiter payload bay. The pressurized carriers will transport equipment and supplies which require a pressurized, protected environment. Unpressurized carriers will be used for liquids and equipment which need no pressurization. Both kinds will be reusable.

The pressurized logistics carrier will be located on the nadir of the Station (in the direction of the Earth), berthed either at Node 1 or Node 2. It will be approximately 14 feet in diameter. Its length has not yet been determined. The pressurized logistics carrier will be structured like the nodes and modules. The primary structure will consist of a cylindrical pressure shell with conical ends. It will have both Orbiter and Space Station attachment mechanisms. The secondary structure will consist of a rigid surface for the support of distributed subsystems and utilities, secured stowage, and facilities for interchangeable racks containing spare parts, Orbital Replacement Units (ORUs), experiment parts, and consumables. (Orbital replacement units are modular components of the Space Station that can be easily taken off and replaced.)

The unpressurized logistics carrier will also berth at Space Station ports. It will be designed to carry equipment and supplies that do not require a pressurized, protected environment. This could include ORUs for the Space Station, Station payloads and experiments, and fluids.

A family of designs is being studied for the unpressurized logistics carrier. It will be roughly cylindrical, but size and exact structure of the module has not yet been determined. The diameter will be no wider than the diameter of the Orbiter cargo bay. The length may vary according to the purpose of the particular carrier.

8. Airlocks

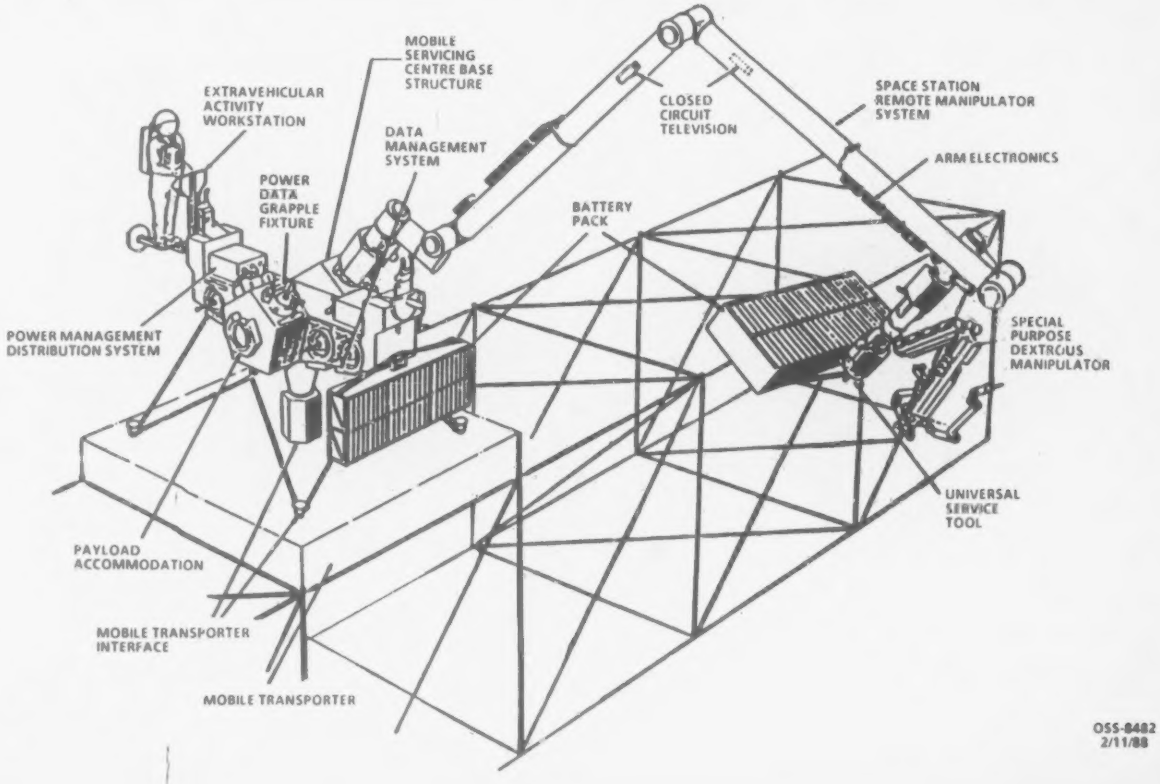
There will be three airlocks on the Space Station: two pressurized at normal sea-level pressure, and one hyperbaric airlock capable of functioning at higher pressures. The airlocks will allow a suited astronaut to enter and exit the protected environment of the Space Station. They will provide depressurization and repressurization, EVA system checkout, service and maintenance equipment, and EVA system storage. The airlock will have access to all the distributed systems and utilities provided to other pressurized areas of the Space Station.

The hyperbaric airlock is a variable pressure airlock that will be used in the event that a crew member needs medical attention for conditions such as altitude decompression sickness or pulmonary embolism (the "bends"). Provisions will also exist to pass items to and from the vacuum of space without loss of pressure in the Space Station. Both kinds of airlocks will be structured like the other pressurized Space Station modules.

9. Mobile Servicing System

The Mobile Servicing System (MSS) will be a automated tool used for assembly, routine servicing, and maintenance of the Space Station and attached payloads. See Figure 6.

Figure 6
MOBILE SERVICING CENTER


MOBILE SERVICING CENTRE BASE STRUCTURE
EXTRAVEHICULAR ACTIVITY WORKSTATION
DATA MANAGEMENT SYSTEM
POWER DATA GRAPPLE FIXTURE
CLOSED CIRCUIT TELEVISION
SPACE STATION REMOTE MANIPULATOR SYSTEM
ARM ELECTRONICS
BATTERY PACK
POWER MANAGEMENT DISTRIBUTION SYSTEM
SPECIAL PURPOSE DEXTROUS MANIPULATOR
UNIVERSAL SERVICE TOOL
PAYLOAD ACCOMMODATION
MOBILE TRANSPORTER INTERFACE
MOBILE TRANSPORTER

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The Mobile Remote Servicer (MRS), provided by Canada, and the U.S.-provided mobile transporter (MT) will make up the Mobile Servicing Center (MSC). The MSC will be the primary element of the Mobile Servicing System. The MT will ride along rails mounted on the truss, providing mobility for the MSC. The MT will alsogenerate its own, or throughput Space Station distributed utilities and data. The base of the MT will measure approximately 16x20 feet. The height has not yet been determined.

The MSC will consist of a base structure mounted on the mobile transporter, a Remote Manipulator System (RMS) similar to the one on the Orbiter, an Astronaut Positioning System (APS), and a Special Purpose Dexterous Manipulator (SPDM) which acts as the "hands" of the system. The APS will be similar to the RMS, except that it will have additional restraints designed to secure a suited astronaut. The SPDM will be designed to perform changeout of Space Station Orbital Replacement Units (ORUs) and attached payloads.

In support of construction and assembly functions, the MSS will remove cargo from the Orbiter cargo bay, transport it to the point of construction or assembly, support EVA assembly functions with flight crew positioning devices, and provide post-assembly inspection. The MSS will also transport Station elements and payloads to locations on the Space Station as well as provide deployment and retrieval functions. It will also support EVA operations and Space Station maintenance.

10. Flight Telerobotic Servicer

The FTS will be a highly automated telerobotic device capable of precise manipulations in space. Phase B Preliminary design for the Flight Telerobotic Servicer is currently underway. Thus, while a functional description is possible, a physical one is not yet available.

The FTS will do routine and hazardous tasks, thereby reducing EVA time and risk. Proposed initial capabilities include installation of truss members, installation of fixtures on the truss, changeout of Space Station ORUs, the mating of the Space Station thermal utility connectors, and inspection tasks.

Astronauts will operate the FTS using both direct manipulator control and programmed command sequences. The FTS will be designed to be operable from several different workstations as the Space Station develops. Its hardware and software will be structured in a modular fashion to ensure serviceability, and its configuration will be flexible enough to facilitate technological upgrade.

11. Attached Payload Accommodations Equipment

Attached Payload Accommodations Equipment (APAE) will be the equipment used to mount and run external scientific payloads. The APAE will include a structural interface between the Space Station and the payloads, and distributed systems outlets to supply the payloads with power, fluids, energy, and data links. The APAE will be designed to accommodate a variety of external payloads, from pre-integrated instrument pallets, to single instruments requiring gimbaled pointing.

There will be two sets of attached payload accommodation hardware that can be used at any of the four utility ports (also called attach points) located along the transverse boom. In addition, there will be one precision pointing mount furnished at any one of the four locations for instruments which must be oriented continuously in a specific direction.

12. Propulsion Assembly

The propulsion assembly will provide thrust for orbit maintenance and three-axis thrust for attitude stabilization and reorientation. That is, three-axis thrust will be used to desaturate the Control Momentum Gyroscopes (CMG) which are the primary attitude actuators of the Stabilization and Control System (S&CS).

The propulsion system will consist of four propulsion modules, a tank farm, and a fuel distribution system. Each module will contain fuel tanks, plumbing and valving, a fuel pump, and two types of jet actuators. The hot gas actuators provide thrust for orbit maintenance. They will be in the 25-40 pound thrust range and will be fueled by a hydrogen/oxygen mixture. The smaller engines used for vernier control will be resistojets in the one pound thrust range. The central tank farm will consist of tankage, valving and a distribution system to the propulsion modules.

C. Space Station Distributed Systems

Distributed systems are those systems whose end-to-end performance is located in two or more elements.

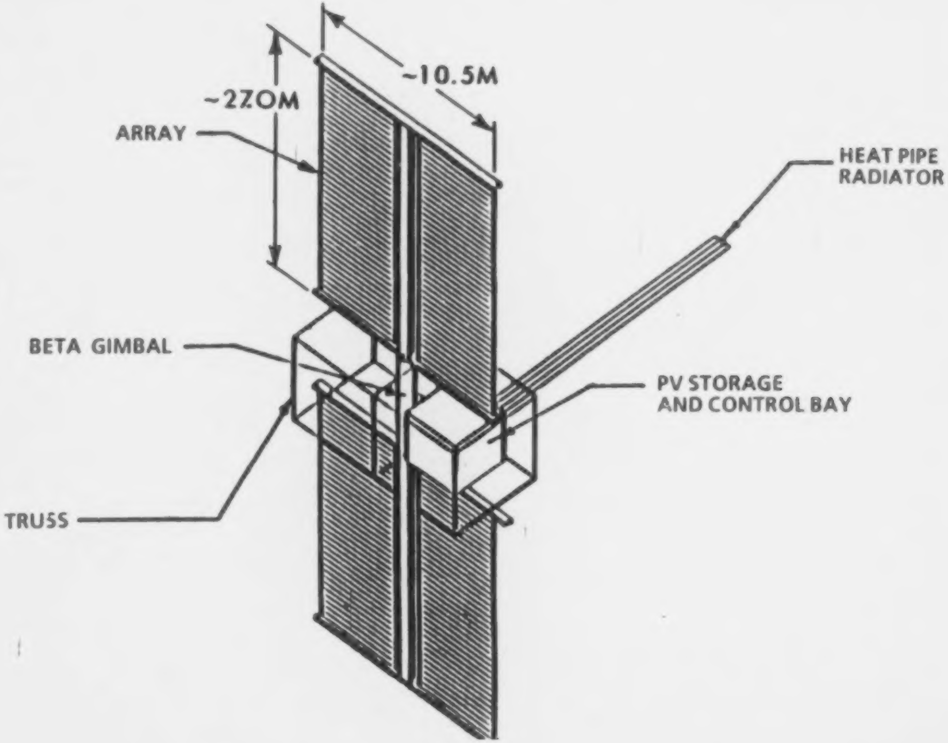
1. Electrical Power System

The electrical power system is a distributed system which will generate and distribute 75 kilowatts (kW) of electrical power to the Space Station housekeeping functions and users. The system will consist of two power modules and a distribution and management system. The power modules can be considered a separate element, but because they are an integral part of the overall power system, they are described here.

The power modules will be located at each end of the transverse boom. The primary structure of the power module will be a truss similar to the boom construction. Each power module will be composed of two pairs of photovoltaic solar arrays. The module will be attached to the boom with a rotating mechanism, the alpha joint, which will provide 360 degrees of rotation to angle the solar array panels toward the Sun as the Station revolves around the Earth. Each solar array will be attached to the power module structure with a beta joint. This joint will provide a second degree of freedom necessary to permit the solar panels to track the sun. The solar panels will be approximately 10.5 meters wide and 27 meters long (see Figure 7).

The power modules will contain nickel hydrogen batteries to store the direct current (DC) power generated by the solar panels for use when the Space Station is in the shadow of the earth. Each power module will also contain power converters to convert direct current to 20 kHz alternating current (AC) for distribution throughout the Space Station. They will also have radiators to dissipate waste heat from the power module.

Figure 7
PHOTOVOLTAIC (PV) POWER ARRAY


~10.5M
~27OM
ARRAY
HEAT PIPE RADIATOR
BETA GIMBAL
PV STORAGE AND CONTROL BAY
TRUSS

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The distribution equipment will include cables, load converters, transformers, regulators, switches and other standard electrical equipment. The overall distribution subsystem will be composed of equipment necessary to process, control, and distribute power to other Station subsystems, elements, and attached payloads.

The electrical primary distribution architecture calls for a modified dual-ring bus system which provides utility power to external areas. Each of the four manned modules will be supplied through one or more resource nodes. Transformers will be used at the node penetrations to provide isolation for the single point ground system and to reduce voltage to the standard value supplied.

2. Thermal Control System

The Thermal Control System (TCS) will control the temperature and heat distribution throughout the Space Station, and vent the heat produced by on-board systems. It will be composed of two parts: a Passive Thermal Control System (PTCS) and an Active Thermal Control System (ATCS). The PTCS will consist of thermal blankets and reflectors which will isolate Station components from the temperature extremes of the space environment. The ATCS will supplement the PTCS.

The ATCS will collect, transport, and reject waste heat from the manned modules and other Space Station elements. The central heat collection and transport will be accomplished using a thermal bus approach. The thermal bus will use a two-phase working fluid to transport heat by evaporation and condensation. This will provide a distributed heat sink function at a constant temperature over the length of the flow circuit. Ammonia and water will be the two working fluids. Ammonia will be used in the parts of the Station external to the manned modules, and for safety reasons, a water loop connected to the ammonia loop will be used internally. The internal loop will operate in the range of 35 degrees Fahrenheit, the external loop, in a range of 70 degrees Fahrenheit. These two central flow circuits in turn will interface with a modularized, erectable central heat pipe radiator system. This radiator assembly, located on the transverse boom, will include a rotary fluid joint that permits the radiator to be rotated away from the radiant heat of the sun.

ATCS control functions will be automated as much as possible to minimize requirements for crew participation. System operating parameters such as pressures, flow rates, and fluid temperature could be controlled by automatic control valves and sensor feedback systems. General system condition, fault detection/isolation, and redundancy management could be controlled automatically in event of component failure. The automatic controller could perform the necessary data processing with standard data processors supplied by the Data Management System.

3. Space Station Information Systems

Space Station information processing and communications capabilities will be accomplished with a network of related systems, collectively called the Space Station Information System (SSIS). Using the on-board Data Management System (DMS) and the Communications and Tracking System (C&T), the SSIS will provide for information flow within the Station for housekeeping and user purposes, as well as to and from earth.

Technically, the Space Station Program-provided portion of the SSIS will be part of the Station infrastructure. As such, it is not entirely a distributed system of the Space Station because many of its component systems will be located on Earth. Nevertheless, it is an integral part of the Space Station program.

The SSIS will provide communication transparency to both the users and operators of the Station. This means the user on earth will in effect have a direct link to the Station even though his data signals will be switched through a complex network. Standard formats and data bases, will permit the user to share operational databases and transport software throughout the SSIS.

In order to illustrate the end-to-end operational aspects of the SSIS, the following example traces a flow of operational or experimental data from its origin at the Space Station to the desired ground-based end point (i.e. a user laboratory or NASA ground control). On board the Space Station, the Data Management System will receive, distribute, process and prepare the data for transmittal to the ground. The on-board Communications and Tracking system will process the data, convert it to Radio Frequency (RF), and downlink it via NASA's Tracking and Data Relay Satellite (TDRS) System . TDRS will receive, process and transmit the data to the ground terminal at White Sands, New Mexico. White Sands will receive and demultiplex the data and transmit it to ground control at NASA centers as well as other ground facilities such as users' laboratories. The process will be reversed for ground-to-space communication.

4. Data Management System

The Data Management System (DMS) will be a distributed system of the Space Station. It will also be an integral part of the SSIS. The DMS will be an on-board computer system which will provide the hardware and software resources necessary to support the on-board data processing and control needs of Space Station systems, elements, and payloads. It will also provide a standardized, homogenous operating environment and human-machine interface for both the Station crew and ground operators.

The DMS will provide a family of compatible computers ranging from a single board computer suitable for use as an embedded controller, to a general purpose processor suitable for hosting system application software. Each processor will have a compatible set or subset of the DMS operating system tailored to its specific application.

The DMS will also include a common assembly called the Multipurpose Application Console (MPAC). The MPAC will be the electronic core of the Space Station work stations. It will provide access into operational monitoring, training, testing, caution and warning display, and crew operations. Some of the MPACs will be fixed in place, others will be portable.

5. Communications and Tracking

The Communications and Tracking (C&T) System will also be an integral part of the SSIS infrastructure. C&T will provide all the communications services necessary to support Space Station and payload operations. These will include command and control, audio, video, and telemetry communication and tracking services, both space-to-space and space-to-ground.

The C&T system will be divided into six subsystems, each representing a major class of service or function. The space-to-space subsystem will provide communication with astronauts performing EVA, with the Space Shuttle, the Orbital Maneuvering Vehicle (OMV), the Mobile Servicing Center, the Flight Telerobotic Servicer and any compatible free-flying platforms in the vicinity of the manned base. The space-to-ground subsystem will provide communication via TDRSS to the ground data networks.

The audio subsystem will provide all of the voice communications on the Space Station. It will be a full duplex system similar to a standard telephone system with conference, record and playback capability. It will provide voice communications between the crew inside the pressurized modules, the EVA crew, the crew of other manned vehicles, and compatible ground systems.

The video system will provide all of the internal and external video capabilities on the Space Station. It will be composed of internal and external remotely controlled cameras. The video subsystem will include closed-circuit television, video storage, retrieval, compression, graphics, and special effects capabilities. On-board distribution of video data will be analog, while video transmission to and from Earth will be converted to digital signals. The subsystem will allow special area monitoring, as well as conferencing between crew locations and between crew and ground. There will be signal processor interfaces between the DMS and the video and audio subsystems.

The tracking subsystem will consist of a Global Positioning System (GPS) receiver/processor with provisions to accommodate future laser docking and radar requirements. The control and monitoring subsystem will manage all C&T resources and distribute the C&T data.

6. Guidance, Navigation and Control System

Guidance, Navigation and Control (GN&C) will provide core system control and traffic management. The core system will supply attitude and orbital maintenance, support the pointing of the photovoltaic power arrays and the thermal radiators, accomplish periodic reboost maneuvers, and provide Station attitude and orbital information to other systems and users. The GN&C traffic management function will control incoming, outgoing, and Station-keeping traffic within the vicinity of the Station. It also will control docking and berthing operations, monitor the trajectories of vehicles and objects that may intersect the orbit of the Space Station and support flight planning.

The core GN&C system will consist of inertial sensor assemblies, star trackers, and control moment gyroscopes (CMGs) located on the transverse boom. CMGs act to stabilize the motion of the Space Station. That is, the CMGs will compensate for the cyclical disturbance torques and will accumulate bias torques. Disturbance capability will be limited and unloaded (compensated for) by the propulsion system. The GN&C will also include standard data processors possibly located in two of the resource nodes. The GN&C System will interface directly with the propulsion system thrusters for reboost and attitude control. Orbital state data will be provided by an on-board Global Positioning System receiver/processor via an interface with the C&T system.

7. Extravehicular Activity System

The extravehicular activity (EVA) system will provide crewmembers with the capability to perform routine tasks in the unpressurized environment on and about the Space Station. The system will support assembly, maintenance, repair, inspection, and servicing of Station and user systems.

The EVA system will consist of a number of subsystems. Central to EVA will be the Extravehicular Mobility Units (EMU). An EMU will consist of a space suit, equipment for communications and physiology monitoring, and an autonomous life support system carried as a backpack.

The EVA system will also include a service and performance checkout subsystem, EVA translation and mobility aids such as handrails, slide mechanisms and tethers, and EVA crew and equipment retrieval and retrieval subsystems servicing provisions. EVA lighting, generic tools, miscellaneous support equipment and lockers, extravehicular contamination detection and decontamination equipment, and systems interfaces for airlock, ECLSS, thermal control and power utilities will also be included in the EVA system. These components and subsystems of the EVA system will be stowed throughout the Space Station elements, with the majority of the equipment being located within the airlocks. Various tools, restraints and work platforms will be located on the Mobile Servicing Center. Mobility and translation aids will also be located on the truss.

8. Environmental Control and Life Support System

The Environmental Control and Life Support System (ECLSS) will provide a habitable environment for both the crew and for biological experiment specimens. The system will maintain atmosphere temperature, humidity, pressure and air composition in the pressurized modules. It will supply potable and hygiene water, and process and store biological waste. It will also be capable of detecting and suppressing fires.

The hardware for the ECLSS will be distributed throughout the pressurized elements of the Space Station. Life critical hardware--atmosphere control and supply hardware required for repressurization, fire detection and suppression equipment--will be located in each of the two U.S. modules to provide redundancy.

9. Fluid Management System

The fluid management system (FMS) will distribute fluids such as water, nitrogen, and waste fluids throughout the Space Station.

The integrated nitrogen system will include all of the hardware and software required to resupply, transfer, store, condition, distribute, control and monitor nitrogen for the Space Station. The resupply subsystem will include the tankage, mounting hardware, conditioning, thermal control, transfer, monitoring and control hardware necessary to deliver the fluid to the Station. It will be located on the truss. Tankage and associated equipment to store the nitrogen will also be located on the truss external to the modules. The distribution subsystem from the resupply to the storage systems, and from the storage tanks to the user interface will also be located on the truss. The latter distribution subsystem will consist of two parts. One part will transfer nitrogen to the ECLSS, the integrated waste fluid (IWFS) system, and an interface with the internal distribution systems located in Nodes 1 and 2. The other part will transfer nitrogen to the integrated water system (IWS) and the laboratories.

The integrated water system (IWS) will be conceptually similar to the nitrogen system. It will contain all the hardware necessary to receive, store, monitor and control the water supply aboard the Station. The storage system, located in the nodes, will be able to accept water from the Orbiter payload bay, from the Space Transportation System (STS) water scavenging system, and from the ECLSS.

The integrated waste fluid system (IWFS) will consist of a collection/distribution subsystem, a storage subsystem, and vacuum vent subsystem. These subsystems will contain all hardware and software required to provide for fluid transfer, storage, conditioning, disposal, control, and monitoring to accommodate gas mixtures and water. The collection/distribution subsystem will receive fluids discarded by the users and will transfer them either to the storage subsystem or to the vent subsystem. The storage subsystem will receive most of the fluids and will retain them for periodic transfer to the disposal interface. The vacuum vent subsystem will receive a small amount of the fluids for disposal in a location which minimizes contamination impacts to the Station environment.

The storage subsystem will consist of plumbing, couplings, regulators, valves, compressors, pumps, tankage, filters, and control and monitoring hardware to provide storage and conditioning of gas mixtures and water. The storage subsystem is located on the truss.

10. Man Systems

The Man Systems (MS) on the Space Station will provide all the hardware and systems necessary for crew habitation and a productive working environment. The MS will be distributed throughout the pressurized modules, but most of the equipment will be in the habitation module. The MS will include 14 subsystems: crewquarters; restraints and mobility aids; crew health care; operational and personal equipment; portable emergency provisions; integrated workstations; galley/food management; personal hygiene; illumination; wardroom; stowage; housekeeping/trash management; interfacing partitions and structures; and tools for in-flight maintenance. These sub-systems are being designed taking into account past experience in these areas on the Orbiter and on Skylab.

The crewquarters will provide accommodations for sleep, rest, and relaxation. Each separate crew compartment will also have some storage space for clothing and personal equipment. They will be designed to allow the crew to have a private space away from the open area of the habitation module. The open area will contain the galley and health care units. The galley will contain all equipment necessary for the preparation and clean-up of crew meals. Consumables and supplies will be stored in the habitation and logistics modules. Safe haven emergency supplies will also be provided.

The health care subsystem will provide equipment and supplies to support all medical, health care, exercise, and environmental health needs. The Health Maintenance Facility will be installed in a dedicated area, and will be tied into the DMS and C&T systems. The hyperbaric airlock will be a part of the health care system. The environmental health subsystem will allow assessment of water and air quality, and contamination.

D. Free-Flying Platforms

1. U.S. Polar Orbiting Platform

The polar orbiting platform will be a self-contained free-flying spacecraft operating in a sunsynchronous orbit at near 90 degrees inclination. Depending on its instrument complement, it will perform Earth biological, geological, and oceanographic observations, lower- and upper- atmospheric monitoring and research, solar observations, and plasma physics measurements.

The platform is being designed in a modular fashion so that it can be tailored to specific missions. It will be constructed, as much as is practicable, with components and orbital replacement units that are common with the Space Station manned base. This commonality will allow cost savings, compared with the cost of developing platform components independently.

The platform will have most of the functional systems described elsewhere in this report. The electrical system will use identical or similar components, including photovoltaic solar arrays, nickel hydrogen batteries, and a 20kHz distribution system. The thermal system will be both active and passive, with ammonia as a working medium in a two phase thermal loop. The data management system architecture calls for the use of similar or identical computers and electronic equipment defined in the Space Station architecture. The C&T system will be compatible with the manned base, and all space-to-ground communication will be via TDRSS. The GN&C system will use inertial and stellar sensors, a DMS general purpose processor, reaction wheels for momentum management and attitude control thrusters for maneuvering the platform.

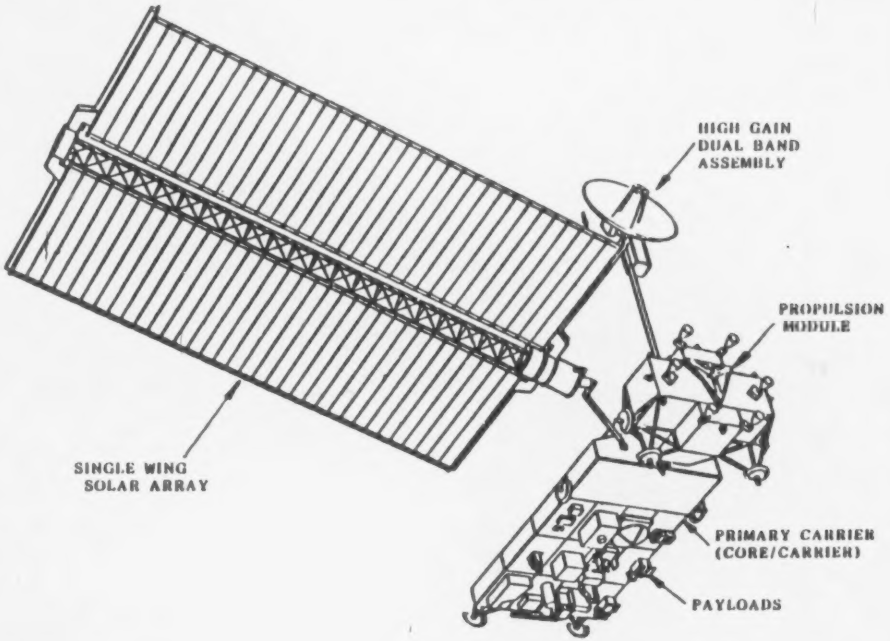
The polar platform will consist of a propulsion module, a primary carrier, and supplemental carriers as required to support user needs. (Figure 8). Overall approximate size will be 46.9 feet (14.3 meters) in diameter, and 39.4 feet (12 meters) long. The primary and supplemental carriers will accommodate both resource ORUs and payloads. The primary carrier may contain resources not supported by supplemental carriers. It will house all of the power generation capability (via solar arrays and drives) and the standard C&T resources. It will also be the interface to the propulsion module. The supplemental carrier will carry payloads and additional resources, such as batteries and data storage ORUs. Thus, the power and data systems for the Polar Platform will be distributed across its carriers. The thermal system of each carrier will be separate, however, with each one being thermally self-sufficient.

2. ESA Polar Platform

The ESA Polar Platform will be an unmanned free-flyer providing standard resources (power, pointing, and communications) primarily to Earth observation payloads requiring a low-Earth, Sun-synchronous orbit.

The platform reference configuration includes a propulsion modules, a utilities and payloads structure, a two-wing-solar array, nickel-hydrogen batteries and radiators, and communications and tracking subsystems. Current studies include backup launch vehicle alternatives, servicing scenario options, and a review of commonality between the platform utilities module and the Man-Tended Free Flyer (MTFF) Resource Module.

Figure 8
U.S. POLAR PLATFORM REFERENCE CONFIGURATION


HIGH GAIN
DUAL BAND
ASSEMBLY
PROPULSION
MODULE
SINGLE WING
SOLAR ARRAY
PRIMARY CARRIER
(CORE/CARRIER)
PAYLOADS

OSS-8484
2/11/88

3. ESA Man-Tended Free Flyer (MTFF)

The MTFF will be an ESA-built, unmanned pressurized laboratory for long duration microgravity applications in the fields of fluid physics, life, and material sciences. It is being designed for launch by an Ariane 5 into a Space Station compatible orbit with periodic servicing at the Station. The initial Station servicing will not occur earlier than one year following completion of on-orbit assembly of the manned base.

The MTFF will consist of a two-segment pressurized module supported by an externally attached resource module. MTFF payloads will be carried within the two cylindrical segments of the pressurized module which will be identical to those of the Columbus Attached Pressurized Module. Inside the pressurized module will be single and double racks, and a workbench available for crew activities during the servicing period when Station-standard atmosphere is maintained. The resource module will supply the basic power, communications and control for the configuration and houses the ORUs containing the subsystems that supply the MTFF and its payloads with resources. Rollout solar arrays and a deployable antenna will be attached. Attitude control will be maintained through liquid propellant thrusters and cold-gas thruster systems.

IV. NASA Analysis of the Report of the Committee on the Space Station of the National Research Council

A. General Analysis

In September, 1987, the National Research Council (NRC) completed its study of the Space Station Program. The NRC Committee on Space Station was asked by the Administration, first to assess NASA's cost estimates for the Station, and second to examine Space Station mission requirements and alternative configurations. The Committee submitted an interim report in June, and a final, more extensive report in September, 1987. The final report consisted of a number of findings and recommendations.

On the whole, NASA agreed with the NRC's conclusions and is incorporating in Space Station planning a number of its recommendations. NASA was pleased that the Committee judged the NASA Block I Baseline Configuration on balance to be the most satisfactory configuration available. The NRC's support for the Baseline configuration provided an important, independent validation of the Station configuration developed by NASA and industry. NASA, however, did not agree with the NRC's conclusions concerning risk and cost.

The NRC found that the Space Station program is critically dependent on adequate space transportation for its assembly and operations, and that deploying the Station with the Shuttle would be difficult and risky. The NRC recommended that the Shuttle be improved with an advanced solid rocket motor, extended on-orbit capabilities, high operational reliability and availability, and provision be made for an orbiter beyond the Challenger replacement. The NRC also recommended that the nation should develop a heavy lift vehicle in the latter half of the 1990's; that NASA should plan for logistics support of the Station with expendable launch vehicles; and that NASA establish a mandatory requirement for a crew emergency rescue vehicle with possible use on a man-rated expendable launch vehicle.

NASA's request in the President's 1989 budget includes an advanced solid rocket motor, extended on orbit capability, provisions for operational support to meet the planned flight rate build-up and further study on crew emergency escape vehicles.

However, NASA does not believe that the deployment of the Space Station with the current Space Transportation System will be "risky". The NRC came to its conclusion in part based on a plan of 18 Shuttle flights for assembly of the Station, which did not reflect changes in NASA planning which occurred late in the NRC review process. In order to lengthen the period of time related to orbital decay, NASA reduced the weights of the first and second payloads and added another flight to the assembly sequence. This modification will enable the current Shuttle system to deploy the first two Space Station payloads at a higher altitude than previously planned, thus significantly lengthening the period of time before orbital decay would occur. This extra time gives NASA a greater margin in which to correct possible problems on the ground before the partially assembled Station would need reboosting.

NASA also disagreed with part of the NRC cost findings. The NRC reduced its confidence in the NASA Space Station costs estimates during its review because 1) the program was still in flux, 2) there were concerns in the application of cost models, 3) the test program cost estimates may be insufficient as some estimates may have reflected a "proto-flight" rather than a "proto-type" test policy, and 4) the Space Station information system and the strategy for automation and robotics was not well defined. NRC also estimated that increases in the test program and for back up hardware could add from $0.2 billion to $3.9 billion to the Station costs. As a result, the NRC recommended that a new cost estimate be prepared in 1988 based upon the Program Requirement Review (PRR). NASA will prepare a new cost estimate as part of the PRR process. The NRC also identified some cost concerns--particularly regarding cost overruns and growth that might arise due to unforeseen technical problems. The NRC also incorporated NASA projections for institutional support, operations, and transportation into its estimate of the program cost. The NASA figure included only development costs (only those costs associated with research and development) in its estimate of how much the Space Station would cost, consistent with NASA practice to divide its budget according to function, as opposed to defining budgetary categories by individual programs. NASA therefore did not include in its estimate of direct R&D costs the related civil service personnel salary costs, new or modified facilities required, or Space Shuttle flight costs budgeted within the appropriations for Research and Program Management (R&PM), Construction of Facilities, or Space Flight, Control and Data Communication, since these are covered elsewhere in the NASA budget.

NASA believes that the Committee's estimate that the upper range of $3.9 billion may be needed for backup hardware is too high. NASA agrees that additional backup hardware will be necessary. It has already identified backup and test hardware needed for the program which would cost approximately $200 million.

The NRC report correctly states that the Space Station represents, and will require, a strong national commitment. This commitment is vital to leadership in civil space endeavors. The President recognized this fact when he directed NASA to develop the Space Station in 1984 and when he asked for a three year advance appropriation from Congress in the FY 1989 budget request. Congress has been equally supportive, providing both funds and guidance. Independent analysis, such as that performed by the NRC, has also been very helpful.

B. NASA Response to the NRC's Findings

The following contains a summary of the NASA response to each of the NRC's specific findings and recommendations.

1. SPACE STATION CONFIGURATION AND ITS RELATION TO MISSION PRIORITIES AND USER REQUIREMENTS

FINDING:

The early scientific and engineering uses of the Space Station are reasonably well understood. No specific defense or commercial applications have been identified.

RESPONSE:

A basic objective of the Space Station program was to ensure that the facility, as designed and built, would be readily accessible and responsive to the needs of the people who would be using the Station. NASA has had extensive interaction with the user communities which has led to an understanding and accommodation of user requirements. The emphasis on utilization depicted during the definition phase will continue throughout the development phase to assure the integrity of a facility that is first and foremost responsive to the science, technology and commercial user communities.

FINDING:

The Block I configuration is a satisfactory starting point for the Space Station. It reflects thoughtful compromises among the priorities and the sometimes conflicting requirements of its early scientific and engineering uses.

RESPONSE:

NASA agrees. NASA and its partners in industry have made a significant effort, both in time and resources, to establish a Space Station configuration that is versatile, and offers a diverse and substantial set of capabilities.

The Space Station will enable an entirely new class of space research, that of doing science in space rather than just the science of space. The major scientific disciplines to benefit from the Station modules will be the material sciences, as well as some research in the areas of basic physics, chemistry, and life sciences. Astronomical and Earth System sciences will also benefit from the Station's capabilities.

While the NRC Committee correctly notes that the Baseline does not provide all that the life scientists may ultimately need, the Space Station is designed for evolution, including the scenario of adding laboratory modules, if needed.

The Office of Space Science and Applications is developing a Space Station utilization plan, projecting both payloads and budgetary requirements for "science in space." In addition, the office is planning to conduct the research and analyses needed to proceed with extended crew times on Space Station of 180 days (and beyond). The NRC Committee states the baseline configuration has no capability for satellite servicing, construction of large space structures, or for staging manned missions to the moon or to the planets. While the baseline configuration (Block I) does not contain a servicing center, this does not mean that there is no capability to service satellites. NASA has initiated a study to determine how the Block I configuration could support satellite servicing with the use of EVA and with the assistance of an OMV. These studies will be traded off against the capabilities of the Shuttle for servicing. NASA has also initiated a study to determine the modifications required to construct large structures in space. Because the Space Station is an evolutionary facility, it can evolve to provide future capabilities as national needs are identified. NASA believes that major servicing of satellites, and large station assembly and staging could be major functions for an evolutionary Station.

FINDING:

In the absence of agreed-upon long-term space objectives, commitment to a particular configuration for Block II at this time would be premature. Indeed, the next phase of the Space Station could go in any of several directions.

RESPONSE:

NASA agrees. NASA has outlined an enhanced configuration, Block II, that illustrates one way the capability of the Space Station could be expanded in the future. With a new national space policy in effect, the Space Station's current design allows for Station evolution that supports this policy.

Concerning the evolution of the Space Station along the lines of those activities enhanced by the Block II configuration, the NRC Committee states that the Space Station will be in the wrong orbit to serve as a good Earth observation platform. The Space Station manned base will cover about one third of the Earth's surface during its orbits around the globe, and potential Earth science programs, could benefit substantially from the manned base orbit. These include the Earth Radiation Budget Experiment, and other future programs that are undergoing study as part of the Office of Space Science and Application's Space Station planning. Scientific requirements will dictate ultimately the proper orbit and platform for scientific instruments, and NASA will ensure the appropriate instruments are placed in the proper orbits. The Earth Observing System (EOS) missions, if approved, require a polar orbit--that is why this important Earth observation program is taking advantage of the Space Station Polar Platform accommodations.

The NRC Committee also states that the upper and lower booms of the Phase II Configuration may not add much to the Station as a platform for science because most important astronomy and solar system exploration experiments can best be deployed on free flying spacecraft. While free-flying spacecraft may indeed be the optimal approach, the additional structure of the Block II configuration does provide useful accommodations. Of course, NASA is planning to use both the Space Station manned base and free flyers for these scientific disciplines. Many experiments are planned for deployment on free flying spacecraft (e.g., Hubble Space Telescope, Gamma Ray Observatory, Advanced X-Ray Astrophysics Facility, Upper Atmospheric Research Satellite, Cosmic Background Explorer, Extreme Ultraviolet Explorer, Galileo, Ulysses, Magellan, Mars Observer, etc.). Many other proposed future experiments within these disciplines are under study which may take advantage of the unique set of capabilities on the Space Station Manned Base.

A servicing capability in space could continue to grow in value and importance. The National Space Transportation System (NSTS) has begun to develop this capability by establishing servicing standards and tools. The success of servicing repairs performed thus far by the NSTS bear witness to the utility of this activity. NASA is preparing a report to congress on satellite servicing. The evolution of Space Station could further advance servicing and serviceability standards and could offer an extended logistics base, as well as the capability for long servicing periods. These assets could be advantageously exploited by some scientific free flyers and potential platforms.

FINDING:

There is no intrinsic operational and little scientific relationship between the polar platform (now included as part of the Block I Space Station Program) and the Space Station. Prospective users of the co-orbiting platforms (part of the Block II Space Station Program) are likely to gain few benefits from man-tending.

RESPONSE:

NASA agrees with the Committee that free-flying platforms should be evaluated on their own merits, whether or not it is a part of the Space Station Program. However, in addition to the scientific merit, NASA believes there is a possible technical and operational advantage of employing a platform which is based on Space Station data, power and control systems. If the scientific community can tap into these resources by essentially using copies of the Space Station systems, then we could develop the next generation of very powerful free-flyers in a cost-effective manner. For the Polar Platforms, these technical advantages are tempered by the lift mass capability to Polar Orbit and the most cost-effective balance is being pursued. For potential co-orbiting platforms, lift mass is not such a driving issue and operational advantages also become available because of the platforms' proximity to the manned base.

The importance of Station platforms to space research is recognized also by our international partners in the Space Station program. The European Space Agency (ESA) intends to provide a polar platform that will operate in a synergistic manner with the U. S. polar platform.

RECOMMENDATION:

The Administration should clarify its long-term goals in space before committing the Space Station a specific evolutionary path beyond Block I.

RESPONSE:

NASA agrees with this approach, and notes that the new space policy sets forth a series of sensible yet visionary goals.

RECOMMENDATION:

Development of those technologies likely to be needed for any evolutionary path, such as solar dynamic power, should be supported.

RESPONSE:

NASA agrees. NASA's current Space Station plan has been to continue technology development and conceptual design activities on the solar dynamic power system at the Lewis Research Center for application to an enhanced Space Station configuration when additional power is required. NASA is working on other advanced technologies in areas such as automation and robotics that may be required for future evolution of the Station. In addition, the new "Pathfinder" program of technology research and development will provide additional technology that could be used in Space Station evolution.

RECOMMENDATION:

The polar and co-orbiting platforms should be evaluated on their own merits, whether or not carried as part of the Space Station Program.

RESPONSE:

NASA agrees. The scientific merit of the polar platform is evidenced by the strong support for the Earth science program from the U. S. science community, NOAA and the international partners. A key element of the Space Station Program, the polar platform will play a vital role in NASA's Earth science program which will try to gain a deeper understanding of the Earth as a system and the consequences of global change for humanity. A U.S. co-orbiting platform is not currently in the baseline program. Any future decision on requirements for a co-orbiting platform will be based on scientific needs and requirements, and the availability of funding.

2. ALTERNATIVE CONFIGURATIONS

FINDING:

None of the alternative configurations for the Space Station examined by the Committee was judged to be as satisfactory as the current Block I configuration.

RESPONSE:

NASA agrees. NASA has spent considerable effort examining alternative configurations for a permanently manned Space Station. During the 21-month long definition and preliminary design activity, intense analysis by NASA and industry provided strong understanding of Space Station design. The Block I configuration is well defined, and has been extensively reviewed. It effectively balances user requirements, fiscal responsibility and program scope.

FINDING:

Man-tended ~~facilities~~ are not substitutes for a permanently manned Station, although they may play a complementary role.

RESPONSE:

NASA agrees. Man-tended Space Stations were examined extensively during the Phase B definition in direct response to the Congress. NASA concluded that a man-tended Space Station would not adequately accommodate all user requirements. Man-tended capabilities are real, but modest; yet they may require substantial funding to be developed. However, the Baseline Space Station assembly sequence does provide a phase where the Station will be man-tended, enabling useful early scientific research to be conducted before a permanent crew is brought aboard.

NASA has the lead for the Administration in efforts to secure a five year lease as an "anchor tenant" on a Commercially Developed Space Facility. Uses of the CDSF complementary to the Space Station are being developed.

RECOMMENDATION:

Block I should be adopted as the initial Space Station configuration.

RESPONSE:

NASA agrees. NASA believes the NRC's support for the Block I configuration provides an important, independent validation of the Space Station design which has been thoroughly studied for over three years and is the baseline design.

3. SPACE SCIENCE AND THE SPACE STATION

FINDING:

Platforms, other than the Space Station, will be needed by space science, even after the Station is deployed.

RESPONSE:

NASA agrees. Scientific requirements, and the availability of funds, will dictate the most appropriate platform upon which science missions should be accommodated.

FINDING:

Devastating blows have already been dealt U. S. space science by the postponement of missions after the Challenger disaster, which followed a decade with very few major space science missions.

RESPONSE:

The Challenger accident was a severe blow to the nation's ability to place payloads in space, including space science missions. NASA is implementing a mixed fleet to reduce the backlog in space science payloads waiting to the launch, and to provide access to space in the future.

FINDING:

Demands for Shuttle launch services will continue to exceed the Shuttle's capacity. This condition will impact scientific access to space.

RESPONSE:

NASA's recovery from the Challenger accident will not take place quickly. It will require time to reduce the backlog of payloads waiting to be launched in the space. Future access to space will be provided by a mixed fleet approach which will provide launch capability for payloads that do not require the Shuttle's unique capabilities. NASA's request in the President's FY 1989 budget includes funding to expand the use of expendable launch vehicles, primarily in support of science missions.

RECOMMENDATION:

Space science should not be confined to the Space Station. Science requirements should dictate the means of access to space. Space sciences should continue to be supported with dedicated spacecraft and expendable launch vehicles after the Station is deployed.

RESPONSE:

NASA agrees. It has never been NASA's intention to confine science payloads to the Space Station nor does the Agency's planning do so. The Space Station will provide substantial and unique capabilities for a variety of scientific disciplines, including life and materials sciences, fundamental research in chemistry and physics, and selected astrophysics, Earth sciences and solar system research; however, the majority of planetary, solar terrestrial and astrophysics activities will continue to be accommodated primarily by means other than on the Space Station. Science requirements should will dictate the best possible platform from which to conduct the mission. Furthermore, NASA is implementing a mixed fleet concept, including expendable launch services to accommodate science missions that do not require the Shuttle or Space Station's unique capabilities.

RECOMMENDATION:

Appropriate NASA offices should assure that timely and sufficient investments for Space Station experiments are made.

RESPONSE:

NASA agrees that Station payloads must be developed in conjunction with the Station. Major user organizations within NASA (Offices of Space Science and Applications, Space Technology) are identifying payload and budget requirements for the Space Station. Private industry, with the support of the Office of Commercial Programs, has also begun planning for utilization of the Space Station. Congress has been supportive in providing funds for this purpose, and we anticipate that funds devoted to Station payloads will be a regular part of future Agency budget requests.

RECOMMENDATION:

In the short to medium term, every effort should be made to increase access to space for scientific purposes. To this end, the on-orbit duration capability of the Shuttle should be increased and expendable launch vehicles should be used for those missions that do not require astronaut involvement.

RESPONSE:

As stated earlier, NASA is implementing a mixed fleet concept for increased access to space. The FY 1989 request includes expansion of expendable launch vehicles services primarily in support of science missions. An unmanned Shuttle-derived vehicle is also being studied as part of the joint NASA/DoD Advanced Launch System. Currently, NASA has the capability to extend the 7-day nominal duration of the orbiter to 10 to 11 days by the addition of a fifth cryogenic tank set to orbiter vehicle 102 (Columbia). NASA will begin the development of a kit to be carried in the payload bay that will extend the Orbiter stay times to 14-16 days.

4. SPACE TRANSPORTATION AND THE SPACE SHUTTLE

FINDING:

The Space Station Program is critically dependent on adequate space transportation for its assembly and operation. Deploying the Space Station with the post-Challenger Shuttle, while not infeasible, will be difficult and risky.

RESPONSE:

While acknowledging the synergism between the Space Station and the transportation system, NASA does not agree with the NRC Committee that deployment of the Space Station with the current baseline Space Transportation System will be "risky." This finding does not reflect the current state of Space Station planning. NASA has reexamined the capabilities of the post-Challenger STS system and has a high degree of confidence that the Space Station can be successfully deployed with the current Shuttle system. In addition, the Advanced Solid Rocket Motor is being initiated in FY 1989 and is expected to be available to support Space Station assembly.

The NRC Committee cites a concern about the relatively short orbital decay times, in the event of a reboost failure, which persists throughout most of the assembly sequence. A detailed examination was conducted by NASA that resulted in the development of a modified assembly sequence that will be utilized to give NASA an even greater degree of confidence in the ability of the STS to successfully assemble and support the Space Station. These data, which delineated the increased margins provided by the modified assembly sequence, were not presented to the NRC Committee in time to be fully evaluated and incorporated into the final report. The 50-day decay time mentioned in the NRC report is based on earlier data that indicated that Launch Package-3 would decay in the order of 50 days in the event of a reboost failure if it were deployed at 190 nautical miles. The revised assembly sequence, provided later to the NRC, indicates that Launch Package-3 would be deployed at 220 nautical miles, resulting in an orbital decay time of 230 days.

The parameters affected in the margin optimization are:

- Assembly altitude.
- The mass margin in each Launch Package.
- The extent that the mass margin is used to deliver payloads.

NASA, of course, will continue to examine and refine launch packages and the entire Space Station assembly sequence. Current studies suggest that Launch Package-4 should also be deployed at 220 nautical miles. The integration of Launch Packages 1-4 will provide a fully quad-redundant propulsion and reaction control system. Once this redundancy is achieved, the probability of a total propulsion system failure is extremely small. Each subsequent Launch Package will be reexamined in order to examine the optimal assembly altitude coupled with the appropriate mass margin.

RECOMMENDATION:

It is highly desirable that the post-Challenger Shuttle be improved in performance while maintaining or increasing its reliability level. Advanced solid rocket motors with improved performance and reliability should be developed for the Shuttle.

RESPONSE:

NASA agrees that the development of an Advanced Solid Rocket Motor (ASRM) would simplify the deployment of the Space Station and provide additional margin. NASA has released requests for proposals for both definition and preliminary design contracts for an advanced solid rocket motor. ASRM development funding is a high priority element of NASA's request in the FY 1989 President's Budget.

RECOMMENDATION:

NASA should assure high operational reliability and availability for the Shuttle, and should establish operational specifications for Orbiter replacement, spares, accommodation of downtimes, and recovery strategy.

RESPONSE:

NASA has established a Headquarters safety program which has developed a centralized safety program for the agency, instituted Level I safety review and approval roles and responsibilities, and implemented a safety program which focuses on prevention. Considerable effort has been put into the review and examination of risk management and assessment. Earlier this year, we conducted a review of risk management functions and techniques used throughout industry which resulted in the assembly of an ad hoc committee of NASA and industry experts to examine various risk assessment methods and applications. Visits were made to Department of Energy (DOE) and nuclear industry contractors to gain further knowledge of Probabilistic Risk Assessment (PRA) techniques. As a result of our efforts in this area, we have established a risk management policy for manned space flight programs and issued a NASA Management Instruction, "Risk Management Policy for Manned Flight Programs" (NMI 8070.4, February 1988). This policy states that the latest proven analytical techniques are to be used in the development and operation of safe and reliable space systems. The policy provides for a variety of quantitative and qualitative analyses and establishes a hierarchy of methods as follows: qualitative methods such as hazard analysis and Failure Modes Effects Analysis/Critical Items List (FMEA/CIL); a hazards categorization and prioritization system based on engineering judgment; qualitative fault tree analysis; and the use of quantitative risk analysis methods where sufficient data bases exist. In FY 1989, we plan to continue to strengthen this area of SRM&QA, including: the completion of a risk management handbook for the NASA centers, a risk management program plan for the NSTS, development and issuance of a risk management NMI for unmanned programs and the development of a risk management NMI for facilities and aeronautical systems.

RECOMMENDATION:

Provisions should be made to produce a Shuttle Orbiter, after the Challenger replacement, for delivery before Space Station deployment begins.

RESPONSE:

NASA has based the deployment and routine resupply of the Space Station on a four-Orbiter fleet. We remain confident that the current fleet is adequate to support the Space Station Program. NASA's mixed fleet concept provides the flexibility to augment the transportation system depending upon user and budgetary requirements. The requirements for additional Orbiters and ELVs will be continually addressed in the future.

As pointed out by the NRC, a robust transportation system is important to pursue an aggressive manned space program.

In addition, NASA believes that a four-Orbiter fleet is required to fulfill the Agency's total space transportation commitments. However, maintaining this fleet demands that a replacement Orbiter plan be established. Two modes may be considered for the replacement orbiter plan. One mode may be the one recommended by the NRC, that is to plan for the periodic replacement of an orbiter. The replacement interval, however, is not determined and may be different than the 5-8 years specified in the NRC report. An alternative, and possibly more cost-effective, concept is to maintain the assembly line by the procurement of a robust spares complement. Initiation of procurement for structural spares is planned for FY 1989.

RECOMMENDATION:

Extended duration on-orbit capabilities should be provided on one or more of the orbiters.

RESPONSE:

NASA will initiate development of an extended duration capability in 1988. One such Orbiter is planned to be modified to carry such a kit.

RECOMMENDATION:

The nation should develop a Heavy Lift Launch Vehicle (HLLV) for use in the latter half of 1990's to permit the launching of payloads larger than those of the Shuttle and to enhance the robustness of the space transportation system.

RESPONSE:

NASA is participating with the Air Force in the definition and development of an Advanced Launch System (ALS). The joint NASA/DoD plan, recently approved by the President, focuses on a new vehicle operational in the late 1990's.

RECOMMENDATION:

NASA should make plans for eventual logistical support of the Space Station with expendable launch vehicles, as well as with the Shuttle.

RESPONSE:

NASA agrees. NASA is currently defining how best to use ELVs to provide logistics support to the Space Station in the mature operations phase of the program.

RECOMMENDATION:

NASA should establish a mandatory requirement for a crew emergency rescue vehicle and should consider its use, on a man-rated expendable launch vehicle, as a backup means of manned access to the Space Station.

RESPONSE:

NASA plans to examine the requirements and configuration of such a vehicle starting in 1988. The requirements for a CERV, the potential application of man-rated ELVs, and other methods for ensuring crew safety, will be identified based on the data gathered during the study phase.

5. SPACE STATION TEST PROGRAM AND BACKUP HARDWARE

FINDING:

The Committee believes that the Space Station test program and backup hardware policy were inadequately defined at the beginning of its study. It believes that NASA has since made progress in both areas, but NASA must continue development of a test program and backup hardware policy, if it is to improve the resilience of the Program.

RESPONSE:

NASA has defined a test program which includes the utilization of flight and flight type hardware, and flight hardware simulators, to verify the preflight integrity of Space Station components and flight packages prior to launch. NASA has also accounted for a large amount of prototype, and a limited amount of protoflight, hardware in the current Space Station Program. NASA will again assess test program and backup hardware plans, utilizing data provided by the Space Station development contractor, during the Program Requirements Review early in 1988.

RECOMMENDATION:

Because of the complex and potentially unanticipated interactions among the Space Station systems, a prototype, as opposed to a protoflight, test program should be employed to the maximum extent practicable. (A prototype program involves the production of two substantially complete sets of hardware--one for ground testing and one for flight. A protoflight program would have only one set used for both purposes).

RESPONSE:

NASA currently has a large amount of prototype hardware, and a limited amount of protoflight hardware, in the Space Station test program. NASA's cost estimates reflect this philosophy of largely prototype equipment for manned elements, and protoflight equipment for the unmanned elements. As part of the Program Requirements Review (PRR) scheduled for 1988, NASA will validate the appropriate application of protoflight hardware considering program risk, cost and schedule.

RECOMMENDATION:

A centralized Space Station Test Bed duplicating, to the extent practical, the configuration of the Space Station on orbit should be retained on the ground.

RESPONSE:

NASA agrees that system test beds which simulate the flight hardware are essential, and a number of them are included in the Space Station Program. The degree to which the test beds are all co-located must be determined based on the capabilities (i.e., vacuum chambers, etc.) current availability, their location, the priorities for new test beds and the availability of funds. Further, NASA is examining options for using the Commercially Developed Space Facility as a man-tended space test bed, in support of Space Station development activities.

RECOMMENDATION:

Each launch package should undergo pre-launch integration, using the Space Station test bed.

RESPONSE:

NASA has a plan in place to perform prelaunch checkout at the launch site using flight or flight-type hardware and simulators to verify the prelaunch integrity of each launch package.

RECOMMENDATION:

Backup hardware to replace flight equipment that might be lost during the deployment phase should be procured. NASA needs to develop an understanding of contingency scenarios in order to determine the backup hardware required.

RESPONSE:

NASA agrees. NASA will continue, as part of its planning process to assess the need for, and phasing of contingency hardware and long-lead items such as forgings, which would cost approximately $200 million.

6. SPACE STATION COST ESTIMATES

FINDING:

Analyses by the Committee during the second phase of this study have, on balance, decreased its confidence in NASA's cost estimates, as presented in the Committee's June 30, 1987 report. For example, up to $3.9 billion in research and development funds over those noted in its earlier report -- almost a 30 percent increase -- could be needed to enhance the test program and to buy backup hardware. Additional growth could arise from difficulties not now identified. [The NRC reduced its confidence in the NASA Space Station costs estimates during its review because 1) the program was still in flux, 2) there were concerns in the application of cost models, 3) the test program cost estimates may be insufficient as some estimates may have reflected a "proto-flight" rather than a "proto-type" test policy, and 4) the Space Station information system and the strategy for automation and robotics was not well defined. NRC also estimated that increases in the test program and for back up hardware could add from $0.2 billion to $3.9 billion to the Station costs. As a result, the NRC recommended that a new cost estimate be prepared early in 1988 based upon the Program Requirement Review (PRR).]

RESPONSE:

NASA strongly disagrees with the finding. As was addressed in the preceding section on Space Station Test Program and Backup Hardware, NASA has a large amount of prototype hardware reflected in the current cost estimate, and it has developed a cost-effective test plan that properly balances the use of flight and flight-type hardware and simulators to perform preflight and launch package checkout. In the area of concern to the NRC--test program and backup hardware--the only area where NASA can currently foresee a potential cost increase is for procurement of contingency hardware, such as large structural spares, that would be needed in the event such hardware is lost during manufacture, launch or assembly. This additional contingency hardware would cost approximately $200 million. Analysis of the need for this contingency hardware is underway and will be completed at the PRR.

The Committee's report states their review of the cost model used at the Marshall Space Flight Center and the application of this model reduced confidence in cost estimates for Space Station hardware under the control of Marshall. The PRC model used by MSFC is a valuable model that relates NASA prior experience to a future program. Adjustments and weighting factors must be applied in the use of the model for the Space Station based on the applicability of prior experience to the Space Station. NASA believes the MSFC estimates were a valid, useful input to the estimating process. The NASA estimates presented to the Committee resulted from an assessment of several estimates by Marshall and the Johnson Space Center. These estimates more than cover the contractors estimates, plus a reasonable amount of uncertainty in their estimates.

The Committee also stated they did not believe the Space Station Information System was well defined, nor was the related automation and robotics strategy for the Space Station. NASA disagrees with the Committee on these two points. At this time, Program estimates can only be based on system design requirements and detail design concepts. NASA believes that both are well advanced, providing sufficient information available to support the current estimates.

NASA wishes to emphasize that the Space Station Information System (SSIS) is well defined. The SSIS Systems Engineering and Integration (SE&I), which has been based on parallel industry definition studies, has defined the sub-networks (e.g., the Data Management System (DMS), the Communication and Tracking (C&T) System), in considerable detail. The open system approach to networking within the SSIS and our use of international communication standards of the International Standards Organization/Open Systems Interconnect (ISO/OSI) Model and the Consultative Committee for Space Data Systems (CCSDS), are a well founded basis for information flow for the SSP and NASA as a whole.

In the area of automation, NASA envisions greater use of artificial intelligence, expert systems, and other forms of advanced automation as confidence is gained in the technology and applicable areas are identified. In the initial configuration of the Space Station, NASA plans to automate the control of several Space Station resources such as electrical power, thermal management, environmental control and life support, and communication and tracking. For example, power system functions that historically have been done manually will be automated on the Space Station, including activities such as load shifting, bus ties, fault detection and isolation, and system reconfiguration.

It is envisioned that expert systems could play a major role in planning, scheduling, and diagnostics. NASA is pursuing parallel technology development and demonstration program as an extension of the Advanced Development Program and coupled with the technology research sponsored by the Office of Aeronautics and Space Technology (OAST). A major focus of the Transition Definition Program within the Office of Space Station (OSS) is to identify and accommodate automation and robotics capabilities for the Space Station.

As part of the Space Station Program's robotics effort, the Flight Telerobotic Servicer (FTS) will be developed. It will, of necessity, serve as a focal point to nurture all of the technologies associated with Automation and Robotics (A&R). The system is designed to facilitate autonomous operations in the future. In this mode, it will use embedded computers with artificial intelligence software operating under the overall supervision of a human operator.

FINDING:

The level of definition of the Station operations concept does not permit the estimation of steady state operating costs with much confidence.

RESPONSE:

NASA has recognized the need to develop operational cost estimates, and, at the time of the NRC report, had a team developing those cost estimates. These have now been identified and presented to the NASA Administrator. NASA will continue to refine and develop more definitive operations cost estimates.

RECOMMENDATION:

NASA should make a new Space Station cost estimate in early 1988. During this exercise, uncertainties such as those in costs of the test program and for backup hardware should be addressed.

RESPONSE:

NASA agrees. A new assessment of program costs are underway.

RECOMMENDATION:

Increased attention should be focused on estimating and controlling Space Station operating costs, so that these do not absorb a significant portion of the civilian space budget.

RESPONSE:

NASA has focused on operations costs from the beginning of the Space Station program, and will continue to do so. A special report to Congress on this subject was submitted in October, 1987. In addition, in the Fall of 1986, NASA established a special Operations Task Force which has now completed an extensive review of Space Station operations. Copies of that report were supplied to Congress. The report forms the basis of the agency's approach to operations cost management, which is a key dimension of the program's overall management systems. In addition, NASA is developing approaches to establish effective cost control mechanisms for both development and operations to manage the overall program costs within its allocation of funds.

7. MANAGEMENT OF THE SPACE STATION PROGRAM

FINDING:

The management challenge presented by the Space Station Program is at least as critical to the Program's success at its technical challenges.

RESPONSE:

NASA agrees. Given the breadth and depth of the Space Station Program, NASA has put in place a strong and stable organization to manage the program during the detailed design and development phase.

FINDING:

NASA has moved to strengthen Space Station Program management, but additional steps are required.

RESPONSE:

NASA established a new Space Station organization in the summer of 1986 which features a centralized management structure, highlighted by a new technical program office established in Reston, Virginia. NASA will have a strong systems engineering and integration capability, supplemented by a support contractor, to manage the heavily interdependent Space Station work packages. And considering the strong imperative to achieve economy, as well as authoritative central control this organization uses the Field Centers' institutional capabilities and does not attempt to duplicate them. The management and technical structure for the Space Station Program will provide leadership to the project with clear lines of authority and accountability, maximize the use of the capability and competence that resides at each participating NASA Center, efficiently integrate the complex changing conditions during the development process, and result in the development of a safe, reliable and cost-effective Space Station.

The Committee states the provision for integration and test, and component flows among Centers is too complex. NASA recognizes the complexity of the integration, test and component flow process among the Centers, but believes its essential to maximize the benefits of commonality. NASA is continuing to trade-off the cost versus benefit of commonality, and will revisit the inter-Center delivery requirements with the hardware contractors once the development phase of the Program is underway. We expect to be able to provide an orderly solution to this complex issue prior to the PRR which is now targeted to begin in April 1988.

FINDING:

The Committee is not satisfied that the current arrangements to coordinate Space Transportation and Space Station Programs are adequate.

RESPONSE:

NASA recognizes the high degree of coordination that must take place between the Space Flight and Space Station Programs. A coordinating committee, chaired by the Associate Administrators of the respective organizations, has been established and meets regularly. Also planned is a project office-level committee, chaired by the respective Space Flight and Space Station Program Directors, which will meet regularly to identify issues which affect the two Programs and resolve them. In addition, a formal launch and assembly plan for the Space Station will be developed jointly by the two offices.

FINDING:

The Committee believes more attention must be paid to managing the operational characteristics of the Space Station.

RESPONSE:

NASA has examined Space Station operations characteristics, and will continue to do so during development. Operational considerations drove various design requirements, such as the propulsion and life support system. An Operations Task Force reviewed Space Station Operations Plans for six months and has issued its report which serves as a baseline concept for the program. The Task Force's analysis includes a description of key operational functions, a discussion of their inter-relationships, product flows and a review of roles and responsibilities. The Task Force report constitutes a significant piece of Space Station analysis and will provide both a framework and path for our planning. The concept developed by the Operations Task Force is helping better understand, anticipate and control operational costs. NASA has also updated the Congressionally required report on Operations Cost Management. This updated report was submitted to Congress in October. The Plan identifies key operations cost drivers to assist NASA in managing these costs to make the Space Station affordable to use and operate. As stated earlier, NASA is developing approaches for operations management and mechanisms for effective control of operations costs.

RECOMMENDATION:

NASA management must emphasize that the Space Station Program Director is the principal line manager of the Space Station Program and is accountable for the successful development of the Space Station.

RESPONSE:

NASA concurs in this recommendation and that is currently the way the Office of Space Station is structured, based on recommendations made by General Sam Phillips who reviewed Space Station management in detail in 1986. NASA believes this is an appropriate organizational structure to ensure clear lines of authority and accountability, and will constantly reinforce this concept.

RECOMMENDATION:

The Committee recommends that NASA establish a dedicated Space Station project organization that would subordinate all personnel assigned to the Space Station to the Program Director and give the Program Director control of financial and other resources assigned to the Program.

RESPONSE:

The Space Station Program Office in Reston, VA, with subordinate project offices at the Field Centers, was established based on the recommendations of General Samuel Phillips following his review of NASA management. This organizational structure and associated responsibilities were established after review and acceptance by NASA Headquarters and top Center management. The Program Director does control financial and other resources.

RECOMMENDATION:

An improved liaison structure between the Space Transportation and Space Station Programs should be developed as part of the management study called for below.

RESPONSE:

As noted earlier, NASA has taken a number of steps to increase and strengthen the relationship between the Space Flight and Space Station programs, including the establishment of a standing Space Flight/Space Station working group, chaired by the respective Associate Administrators for the two organizations, which meets regularly.

RECOMMENDATION:

An organizational entity, independent of the Space Station development hierarchy, with the ultimate responsibility for operating the Space Station should be formed promptly to assure greater attention to operations during the design phase.

RESPONSE:

General Phillips' review of Space Station management also addressed the need for a strong operations organization and resulted in the Administrator establishing an Associate Administrator for Space Operations. The roles and responsibilities of this new organization are under review at this time. A management plan for the Space Station is being developed which will address operations management.

RECOMMENDATION:

NASA should simplify the structure now envisioned for relations between the Station operators and the users of the Space Station.

RESPONSE:

The relationship between the users and operators was thoroughly addressed as part of a Science Operations Management report which was submitted to Congress last fall, and was also examined by the Operations Task Force. Specific recommendations by members of the scientific community on the mechanism by which science activities should be accommodated and operated on the Station were made in the report. NASA has accepted many of these recommendations and will respond to the remainder in the coming year as the management plan is developed.

RECOMMENDATION:

A realistic Space Station development budget should be determined and funds provided in a series of multi-year appropriations, thereby giving long-term financial predictability to the Program.

RESPONSE:

NASA strongly endorses this recommendation. Multi-year funding would provide the required budget stability to the program and help ensure an efficient, cost-effective development effort. A major proposal by the President in his budget request for NASA in FY 1989 included the request for an advance appropriation commitment by Congress to funding the Space Station for FY 1990 and FY 1991.

RECOMMENDATION:

The Committee recommends that NASA, under the general supervision of the Office of Management and Budget (OMB), conduct a study analyzing the Committee's program management recommendations and concerns. A management plan, expressing how NASA intends to respond to the

Committee's management concerns, should be developed as part of this study. An assessment of NASA's progress against this plan should be carried out at an appropriate time.

RESPONSE:

NASA has reviewed carefully all of the NRC Committees recommendations and findings, including those dealing with management. How the agency responds to these varied suggestions and observations is the subject of this section of the Capital Development Plan. Gen. Phillips' overall management recommendations regarding the Space Station Program have been implemented, and because NASA believes the new Level I - Level II management structure needs to be given time to work. Yet, at the same time, NASA realizes that management policies and practices require continuing examination and adjustment. NASA therefore will hold quarterly budget reviews with the Office of Management and Budget, and plans to prepare, in consultation with OMB, a Space Station management plan and staffing study.

C. Alternative Configurations Presented to the NRC

The NRC examined several alternative configurations, most of which were rejected by NASA for a variety of scientific and engineering reasons. Each of the configurations considered, however, added to NASA's knowledge base, providing stepping stones to the current Space Station configuration. The revised baseline configuration (Block I) was chosen as the best configuration because it offered the best compromise between cost, technical capability and engineering difficulty. This configuration also supports those user requirements that are currently well-defined and that will have near-term fiscal support. In addition, it offers the best foundation from which to begin future evolutionary design paths. Such evolution will occur as specific future mission requirements are identified.

The Baseline configuration represents the lowest cost option for a permanently manned Space Station with significant capabilities. Such capabilities include provisions for human interaction with life sciences and materials processing research. This configuration also allows ample opportunities to learn how to assemble large structures in space--needed for future astronomic observation platforms and for future evolution of a permanently manned base in space.

The following is a description of the configurations NASA presented to the NRC. These configurations focused on those considered in the Space Station Task Force Concept Development Group in 1983-1984. The group included representatives from all NASA centers and 12 contractors. During the 1984 development of the Phase B RFPs for the detailed definition of the preliminary design of the Space Station, 3 of 5 candidate concepts were chosen for detailed study (see Figure 9). The three included the Delta, Concept Development Group - Planar, and the Power Tower configurations. Of these, the Power Tower was chosen as the reference configuration for Phase B. For reasons which will be explained below, the Power Tower concept evolved to the Dual Keel configuration (see Figure 10). Because of budget constraints, the Dual Keel was later scaled down to the present revised baseline configuration (see Figure 11).

The major configuration requirements used as criteria in the selection related to power levels, celestial and earth observational capabilities, growth accommodations, volume and provisions for a crew size of six or more. The configurations were also to have scientific airlocks.

The following is a description of each of the five major candidate concepts, including their primary assets and liabilities. For reference purposes, a brief description of older configurations, representative of space station conceptualization since the 1950s, is also provided. These configurations were also presented to the NRC.

The following two configurations were eliminated early in the examination.

Spinning Solar Array - This configuration would fly in an inertial mode using a large spinning solar array to provide an inherent gyroscopic stabilization. The pressurized modules would be suspended in the center on a bearing which would keep the modules from rotating. The principal advantage of this configuration was its generation of artificial gravity. The configuration also provided structural stiffness to the solar arrays due to the centripetal acceleration they would experience. The disadvantages were numerous. First, the configuration would be nearly impossible to assemble in space, and there would be no way to launch it fully assembled. Second, there would be potential health problems for the crew of continuously adapting to highly different levels of gravity at different parts of the Station. Nor would this configuration provide the optimum microgravity environment for scientific experiments. Third, there was no flexibility of evolution; once assembled, no new power sources or pressurized volume could be added.

Big T - The principal characteristics of this configuration are the gravity gradient stable flight mode and the large solar array with only one degree of movement to track the seasonal variation of the Sun. The Big T would provide a very stiff configuration, and hence, be very stable. The evolutionary capabilities for this space station would be limited, however.

The following three configurations were extensively studied before the start of Phase B.

Delta - This configuration features a large sun-fixed, rotating structure in the shape of a Delta made up of a tetrahedron truss. A large fixed solar array would cover one side of the structure with the inhabited modules attached to the opposite apex of the Delta. The side with the solar arrays would continuously face the Sun by rotating as the station revolved around the Earth. The configuration provided a planar structure for rigidity and attach area.

The Delta configuration's positive attributes included structural stiffness, a large enclosed service area, a large area to attach scientific payloads, no element differential motion, and uniform thermal conditions. Its negative ones included the following: 1) reduced earth viewing at points in the station's orbit; 2) multiple Remote Manipulator Systems would be required to do servicing and other tasks, because a track system to move a servicer would not be feasible; 3) the mass imbalance of the Delta station would have to be nulled by several magnetic torquers; and 4) simultaneous Earth and celestial viewing would be difficult.

Figure 9
CONFIGURATION CONCEPT OPTIONS

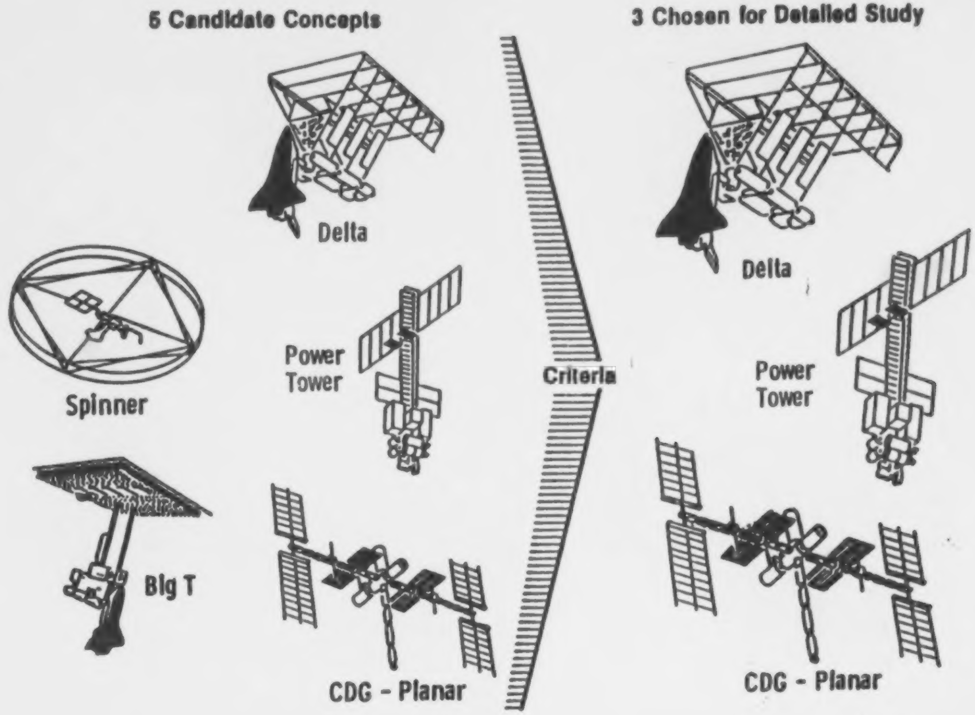

5 Candidate Concepts
3 Chosen for Detailed Study
Delta
Spinner
Power Tower
Criteria
Big T
CDG - Planar
Delta
Power Tower
CDG - Planar

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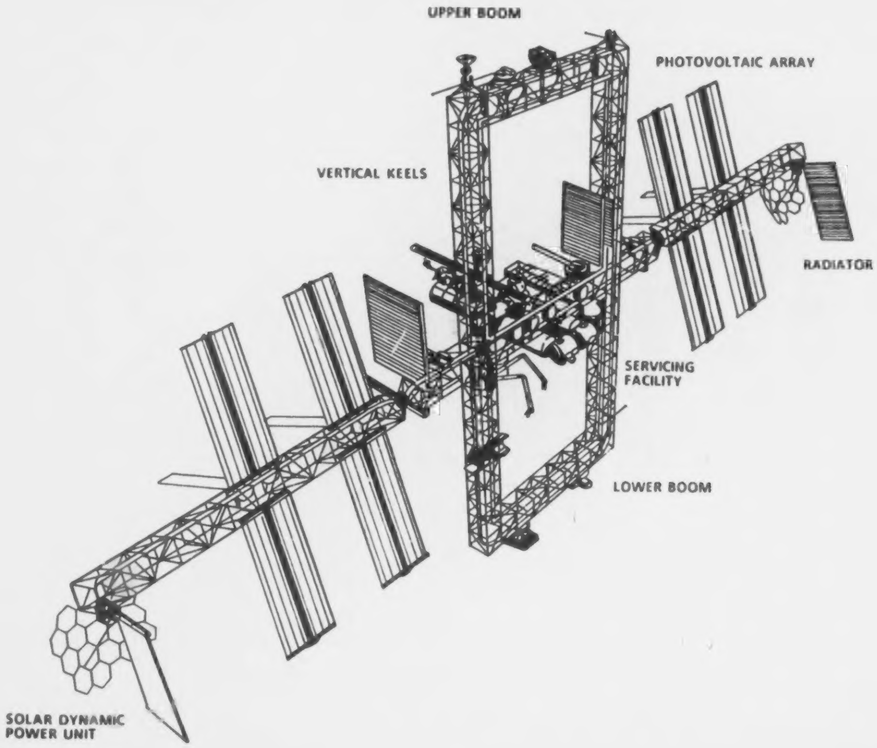
Figure 10
DUAL KEEL CONFIGURATION


UPPER BOOM
PHOTOVOLTAIC ARRAY
VERTICAL KEELS
RADIATOR
SERVICING FACILITY
LOWER BOOM
SOLAR DYNAMIC POWER UNIT

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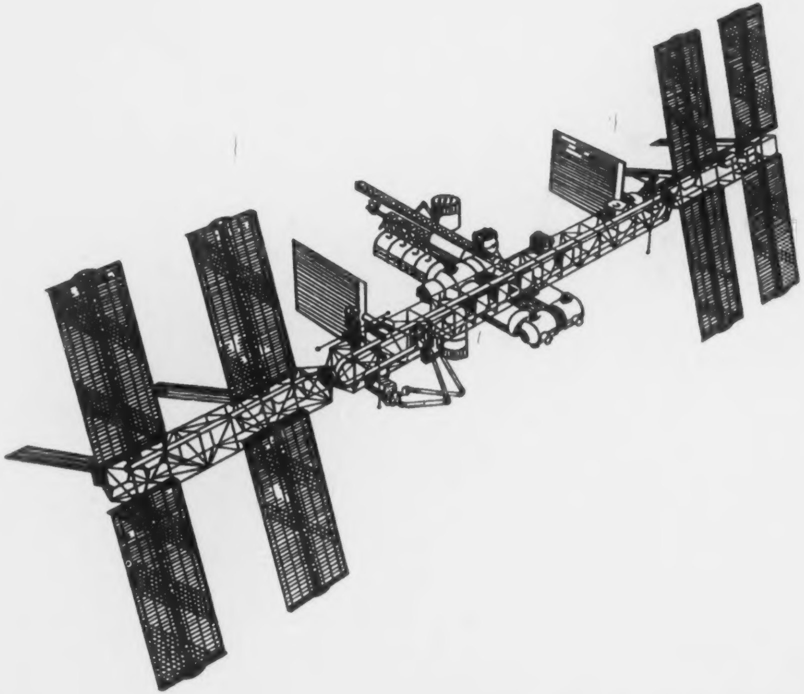
2/11/88

Figure 11
BASELINE CONFIGURATION



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Concept Development Group (CDG) - Planar - This configuration is an inertially stabilized modular design in which pressurized modules would be attached to a transverse structural boom. Power would be supplied by four gimbaled solar arrays. The planar configuration's positive points include having the power and other resources centralized, good orientation and viewing versatility, and relatively easy tether accommodation. Its disadvantages included the following: first, growth would be constrained by requiring symmetry. Second, the Station's solar arrays cannot be pointed continuously toward the sun because of the inertial flight mode of the Station. Third, the position of the solar arrays constrain construction, access, and some viewing. Fourth, special provisions would have to be made to scar the station for future power growth.

Power Tower - This configuration has a single vertical keel, with solar arrays mounted at one end, and the modules mounted to a boom at the other end, closest to the Earth. This arrangement makes it gravity gradient stabilized. Below the modules would be an area to attach Earth-observing instrumentation. The "tower" would rise above the boom to provide a location for celestial-looking instruments. This station is Earth-fixed, or oriented toward the Earth.

The Power Tower has a number of advantages. Its inherent stability makes it forgiving of mass imbalances, so future growth would be simple to accommodate. It could be fairly easily assembled in space. Of the three configurations considered in Phase B, the Power Tower configuration clearly best met the requirement for simultaneous, multidirectional viewing capability. Because of the Power Tower's orientation, communications are also easier to accomplish than they would be with other configurations. This orientation also makes proximity operations relatively easy. Finally, tethers can easily be used with this configuration, it would need less antennas and a simpler system than would the Delta or Planar configurations. The disadvantages are: 1) a potential limit on solar array size; and 2) special modifications would have to be made to scar the station for future power growth.

Of the three configurations analyzed in Phase B, the Power Tower was preferred although all three were considered feasible. All three configurations can be assembled with the Orbiter and a Station Remote Manipulator System. All three could accommodate either solar dynamic or solar photovoltaic power systems. The development costs of the three were considered to be essentially identical. The configurations differ somewhat in dynamics, operations, simplicity of thermal systems, and communications and tracking. For example, dynamically, the Delta requires more control moment gyroscopes (CMG) for stabilization than either the Planar or Power Tower.

Dual Keel - The Dual Keel configuration evolved from the Power Tower concept. The Dual Keel featured a a transverse boom with two parallel keels (see Figure 10). Pressurized modules would be located in the center of the boom. The upper keel would have attach points for celestial-viewing instrumentation; the lower keel would have similar provisions for Earth observation. In addition to the pressurized modules, there would be a servicing facility. The station would be powered by both photovoltaic and solar dynamic power generators.

The Dual Keel has several key advantages. These include its balanced microgravity environment, its extensive observation capability, and its adaptability for future evolution. Structurally, the Dual Keel design materially increased the torsional stiffness of the Station, compared to the Power Tower design, and simplified the necessary guidance and control system. The Dual Keel configuration could also provide housing for an Orbital Maneuvering Vehicle, and later, an Orbiting Transfer Vehicle. It can easily support a space assembly capability.

The main disadvantages of the Dual Keel were the number of flights and amount of EVA time that would be required for assembly.

In addition to these configurations, NASA also presented several that were representative of space station modeling and conceptualization which has taken place since Wernher von Braun's studies in the 1950s.

Manned Orbiting Research Laboratory (MORL), 1966 version - This version of the MORL was designed to use the Apollo logistics system. The Saturn V expendable launch vehicle (ELV) was to be used for delivery to orbit and the Apollo Command Module for resupply. The MORL was to contain a two-man centrifuge in the center of the module for gravity conditioning and biomedical experiments. In addition, the configuration contained a "hangar" to be used as a staging area, supply site, laboratory, and a safe haven.

MORL Brayton Cycle Power System - This configuration incorporated the Brayton Cycle power system. The system was designed to produce 11 kW of power. This design also included an extended skirt to provide the increased radiator area required by the power system.

Large Space Station Concept - This configuration, designed in 1967, was proposed as a post-Apollo and Skylab space Station. The station was envisioned as a large-scale facility supporting a crew of 75 to 100. Artificial gravity would be provided (1-g) by spinning the station at 3.5 rpm. This station was designed to be 33 feet in diameter, and carried by the Saturn V ELV.

Phase B Modular Space Station - This configuration, was developed in the early 1970s after a decision was made to develop the Space Shuttle. The modules were to be 14 feet in diameter, and were to be delivered by the Shuttle.

Space Operations Center (SOC) - This was a joint effort by Boeing Aerospace Co. and Johnson Space Center. This design was also modular and Shuttle serviced. The SOC was to be a low-Earth satellite primarily designed for space-based construction and servicing. Intended for evolutionary growth, the crew size for this configuration was to increase from 4 to 20.

The NRC looked at one other configuration, The Harwood Space Station Concept Proposal. This concept was not presented by NASA.

The Harwood Concept - This configuration was made up of equal length elements configured into a large tetrahedral truss. Each member was approximately 57 feet in length (the maximum allowable length in the Shuttle bay) with pressurized modules interspersed with the structured elements. The concept had the advantage of being able to grow to any desired size. It had several major disadvantages, however. The elements were too long to be assembled by the Shuttle. The concept also showed no plan for integrating power systems and thermal radiators into the configuration, and if they were added, would require relocation at each stage of growth. The configuration did not support payload mounting and pointing requirements. Finally, contrary to Harwood's claims, there was no evidence that this configuration would cost less than the NASA baseline.

NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546

Reply to Attn of: XC:JM:drg

MAY 26 1988

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

RECEIVED
MAY 25 1988

Dear Mr. Chairman:

During the hearing of March 30, 1988, the Subcommittee on Space Science and Applications requested that NASA provide to the Committee its microgravity strategic plan. NASA is currently in the process of developing a comprehensive microgravity strategic plan which will be transmitted to you in the near future.

As requested in the House of Representatives Report No. 98-65, Authorizing Appropriations to the National Aeronautics and Space Administration for Fiscal Year 1984, dated April 15, 1984, the Committee requested the submittal of an annual report on the NASA Microgravity Science and Applications Program. The enclosed document is being submitted to present a review of NASA's Microgravity Science and Applications Program.

The report entitled, "Microgravity Science and Applications Division--A Program Overview: 1986-87," summarizes the program's activities and includes a detailed description of the research program as well as key planning and review efforts. This report is intended to fulfill the 1986 and 1987 requirements for an Annual Report for Materials Processing. The plan presented in the enclosed report provides the goal and objectives, which have guided the program over the past two years.

Although there has not been an opportunity to conduct flight experiments on the Shuttle in the past two years, NASA has continued to conduct an active research program by utilizing ground-based facilities such as droptubes, droptowers, and the KC-135 aircraft. In addition, the interim period has been used to review the program and to implement key changes for ensuring a more focused, thus strengthened, program. NASA is very enthusiastic about the future of the Microgravity Science and Applications Program and looks forward to presenting continued program accomplishments in future reports.

As the Agency responds to the President's new National Space Policy, our existing plans will be modified to incorporate input from NASA advisory bodies, other NASA offices, other Government agencies, and industry participants to formulate a comprehensive NASA Microgravity Strategic Plan.

NASA will be pleased to brief you and your staff on this annual report at your convenience.

Sincerely,

Jon A. McBride
Assistant Administrator
for Congressional Relations

Enclosure

cc: Honorable Manuel Lujan, Jr.

MICROGRAVITY SCIENCE AND APPLICATIONS DIVISION

A Program Overview: 1986-87

National Aeronautics and Space Administration
Washington, DC 20546

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Appendix: Acronyms and Abbreviations

I.

INTRODUCTION

Since the late 1960's the National Aeronautics and Space Administration (NASA) has been committed to researching the effects of low-gravity conditions on materials and processes. As scientists first conceptualized how to design a spacecraft to operate in the orbital environment, the need to examine the near absence of gravity that results from the free-fall conditions of orbital flight became a key research challenge. For example, not only did scientists need to research the behavior of fluids in the low-gravity environment to design effective and safe propellant systems, but questions concerning fire safety and the fabrication of structures in space also required significant examination.

Today, decades later, as the U.S. Space Program moves toward the Space Station Era, NASA's Microgravity Science and Applications Division (MSAD) program has evolved to encompass seven research areas and to include the participation of over 135 researchers affiliated with over 60 public and private sector organizations. In addition, as the program continues to pursue the traditional science-based objectives, there is a parallel effort to design and develop the supporting experimental equipment and facilities that will evolve for use on the Space Station.

In 1983, the House Committee on Science and Technology, recognizing the potential application of space-based materials processing, requested that NASA submit an Annual Report describing current and future program activities. This report is intended to respond to that request and presents an overview of MSAD's 1986 and 1987 program activities.

Although the 1986 Challenger disaster brought an abrupt halt to the MSAD flight program and continues to delay that aspect of the research program, the interim period has been productively used to reassess the past microgravity program and to implement several, new, significant program thrusts. This two-year overview of the microgravity program discusses key planning activities, review committee recommendations, current program activities, and commercial, interagency, and international activities.

Although new and still somewhat fragmented, Microgravity Science has emerged as a recognized research discipline with considerable scientific and commercial potential. To maximize the return from this research it is important to build the requisite technology base and to conduct a high-quality science program. Both of these elements are predicated on the active participation of the broadest research community. There is a strong parallel between U.S. leadership in exploration, the development of the space frontier, and the continued ability of the United States to compete technologically and economically in the future.

One of the most significant review efforts, lead by Dr. Bonnie J. Dunbar, focused solely on NASA's Microgravity Program. The results of the NASA Microgravity Materials Science Assessment Task Force effort became available early in 1987. A major recommendation was to develop advanced multiuser or facility-class scientific hardware for use on the Space Station or a Commercially Developed Space Facility (CDSF). The Task Force also strongly endorsed the increased utilization of Spacelab and microgravity-dedicated primary payloads. Several valuable recommendations concerning program organization, interagency coordination, strategic planning, resources, and policy were provided by the Task Force.

A committee chaired by Nobel Laureate, Robert Schrieffer reviewed the Microgravity Science and Applications flight program and published its findings in a report entitled, *Review of Microgravity Science and Applications Flight Programs: January–March, 1987.* Published in October of 1987, the Schrieffer Committee recommendations specifically deal with the quality of the research projects, potential for scientific and commercial impact, questions of access to space and flight priority, as well as suggestions concerning ground research and overall program management.

The recommendations presented by the NASA Microgravity Materials Science Assessment Task Force and the Schrieffer Committee have provided NASA management with a stronger, more balanced program approach for the development of near-Earth space as a national resource.

In addition to conducting these planning activities, the extensive ground-based research program continued at a high level of activity. This involved significant use of droptubes and droptowers as well as the KC-135 aircraft.

The following chapters elaborate on the results of key planning efforts, provide an overview of the 1986 and 1987 research program, and summarize our commercial and international activities.

II.

PLANNING ACTIVITIES

Over the past two years, three key planning activities were performed to provide recommendations for guiding the future of NASA's Microgravity Science and Applications Program. The result of one activity, MSAD strategic planning, was the identification of the key program elements required to accomplish program objectives. A second activity, the Discipline Working Groups planning effort, involved participation of academic, government, and industry scientists to define long-range science objectives and research priorities. A third effort, MSAD Flight Project Management Planning, involved NASA Field Center participants and resulted in establishing policy and procedures for experiment hardware and facilities development. This chapter presents a discussion on the MSAD strategic plan and Discipline Working Groups' effort. The Flight Project Management Plan is presented in Chapter VI, Flight Facilities Development.

NATIONAL POLICY: NASA STRATEGIC PLANNING

In February 1988, President Reagan issued a new National Space Policy. At the same time the President also articulated a Commercial Space Initiative that is expected to have a profound effect on the planning activities already underway or near completion. To respond to this new policy, the planning base discussed in this report will be integrated with input from NASA advisory bodies, other NASA offices, other government agencies, and industry participants to formulate a comprehensive NASA Microgravity Strategic Plan. While the strategic plan discussed in the following section has provided the basis for the activities presented in this report, it is expected to be only one of several vital elements required in the new plan.

SPACE SCIENCE AND APPLICATIONS: MSAD STRATEGIC PLANNING

The Associate Administrator for the Office of Space Science and Applications (OSSA) requested each Division Director to prepare and submit an annual strategic plan. These division-level plans have been integrated into the 1988 OSSA Strategic Plan. Recent developments in space commercialization will require that the existing MSAD strategic plan evolve to incorporate new program options and resource requirements. The comprehensive strategic plan will be available soon.

The current strategic plan is the product of an iterative, division-level planning process that can be adapted to changes in resource availability, mission, and other factors. As a result of the MSAD strategic planning process, organizational goals and objectives were established, resource requirements and allocations were specified, and environmental factors that can affect operations were assessed.

The overall goal of the Microgravity Science and Applications Program is to develop near-Earth space as a national resource. In this unique environment it will be possible to:

- Advance fundamental science that governs processes on Earth, in the solar system, and in the universe.
- Increase the understanding of the influence of gravity on Earth-based processes thus leading to better control strategies for such processes.
- Produce limited quantities of exotic, high-value materials with enhanced properties to serve as benchmarks for comparison with Earth-based technologies or for highly specialized applications.
- Evolve processes for the eventual commercial production of certain high value-added products in space.

To achieve these advances, it is necessary to develop the requisite infrastructure to facilitate the efficient use of near-Earth space by researchers from the academic community, government, and industry. This infrastructure requires a coordinated and involved research community, well-conceived research plans, state-of-the-art hardware, and, most importantly, frequent and economical access to the near-Earth space environment. The MSAD strategic plan provides a framework for more detailed operational planning, resource allocation, and program management.

Key elements of the current MSAD plan are to:

- Expand the microgravity user community through the development of a relevant data base, and effective dissemination of information concerning the advantages and limitations of the space environment.
- Facilitate and expand the participation of the industrial, government, and academic research community in formulating, conducting, and applying microgravity research.
- Promote a high-quality science program through expansion of the ground-based research and periodic review of the flight experiments
- Assure the most efficient and effective use of limited flight opportunities through collaboration with commercial users, development of multiuser hardware, and coordination of flight manifest priorities.
- Enhance the quality and yield of research data through the development of state-of-the-art flight hardware and instrumentation that can be adapted to the available carriers.
- Establish the Space Station as a national laboratory and effectively utilize available carriers and platforms to evolve and refine Space Station capabilities.

DISCIPLINE WORKING GROUPS' LONG-RANGE SCIENCE PLANNING

For almost two years, a NASA-sponsored group of scientists from government, industry, and academia convened periodically to identify research priorities for microgravity in their respective disciplines and to identify gaps in the present program. These Discipline Working Groups (DWGs) have been organized to examine Electronic Materials, Metals and Alloys, Glass and Ceramics, Fluid Dynamics and Transport Phenomena, Combustion, and Biotechnology. A seventh group to review Polymer Science is being organized in response to industrial and academic interest expressed at the Space Station Utilization Conference held in Nashville in November 1987.

To date, the DWG activity has resulted in a draft report that outlines for each discipline a goal, objectives, supporting rationale, applications, and a summary of the current program. These DWG inputs together with inputs from the NASA-internal Microgravity Science and Applications (MSA) Science Panel, a group of scientists from the various NASA Centers, will be considered in determining gaps in the present program as well as a list of high-priority or "burning" issues that must be resolved in order to establish the feasibility of certain processes or areas of research.

These issues will be discussed at a three-day workshop involving members of the Space Applications Advisory Committee's (SAAC) Microgravity Science, Applications, and Commercialization Subcommittee, who may suggest additional issues and recommend priorities for the research. The SAAC workshop activity is scheduled for May with a report tentatively scheduled to be published in the September 1988 timeframe.

Following the identification of the high-priority issues, MSAD in conjunction with the Office of Commercial Programs (OCP) will publish a NASA Research Announcement (NRA) that will address these issues. This will provide a directed research program to supplement the existing broad-based research program.

III.

NASA MICROGRAVITY MATERIALS SCIENCE ASSESSMENT TASK FORCE

Several major impacts on the MSAD's program have resulted from the NASA Microgravity Materials Science Assessment Task Force (NMMSA) effort headed by Dr. Bonnie Dunbar. The most significant of these is the implementation of the Task Force's recommendation that a series of Spacelab missions be dedicated to microgravity materials research in order to develop elements of facilities for eventual use on Space Station and to provide an early science return.

The first flight of this U.S. Microgravity Laboratory series (USML-1) has been manifested for March 1992. Subsequent flights are scheduled for alternate years between the International Microgravity Laboratory (IML) missions to provide a series of microgravity emphasis flights on a regularly scheduled basis. This will provide a continuity to the flight program that has been badly needed.

The original concept of using the Materials Science Laboratory (MSL) carrier in the payload bay as a secondary payload with minimum Shuttle interface on flights of opportunity has not been as productive as originally planned. Because of the manifesting changes and the low priority of secondary payloads, only three flights of the MSL have taken place (STS-7, STS-61A, and STS-61C). The prospects for MSL opportunities as secondary payloads in the post-Challenger era do not appear to be much brighter even though a considerable hardware inventory to fly on MSL has been developed.

The use of Spacelab missions in which microgravity science is the primary mission has an additional advantage in that the flight rules can be set to minimize residual accelerations and disturbances. Recent analysis has shown a much higher sensitivity of certain experiments to such residual accelerations than had been anticipated and, in fact, it may be necessary to align furnaces along the residual acceleration vector caused by atmospheric drag and gravity gradient effects in order to achieve diffusion control. This can only be ensured on microgravity-dedicated flights. It also appears that the MSL carrier can be flown behind the Spacelab module to accommodate experiments that have modest power requirements.

Another major recommendation of the Task Force was to develop facility-class hardware that could be developed and proven during the USML series of flight and that ultimately would be used on the Space Station or a CDSF. These facilities would replace the obsolete hardware that was modified from the old Space Processing Applications Rocket (SPAR) program in order to take advantage of early Shuttle opportunities. This hardware, which had limited capabilities and has proven to be less than reliable, has now been retired.

Six new facilities have been identified that will accommodate most of the experiments identified for Space Station in the Microgravity Materials Processing Facility (MMPF) study recently completed by Teledyne Brown Engineering. The facilities, which were initiated in FY 1988 and included in the funding request for the program in FY 1989, are the Modular Multizone Furnace Facility, the Modular Containerless Processing Facility, the Advanced Protein Crystal Growth Facility, the Biotechnology Facility, the Fluid Physics/Dynamics Facility, and the Modular Combustion Facility.

In addition, two additional areas of experimentation, polymer science and fundamental physics and chemistry are being planned. Currently, it has not yet been determined whether such experiments could be accommodated in existing facilities or if new facilities will be required. Detailed descriptions of the facilities are provided in Chapter VI, *Flight Facilities Development*.

The Task Force also recommended changes in the organizational structure of NASA that would foster a closer coordination of the internal microgravity activities. A Decision Memorandum was issued by the Deputy Administrator delineating the division of roles and responsibilities between OSSA and OCP to ensure this coordination. A Presidential Executive Exchange Program appointee with a strong industrial research background has been assigned to MSAD to act as a liaison for commercial programs.

An Implementation Plan has been developed detailing the interactions of the two organizations. Essentially, OCP will continue to act as the focus for all commercial activity and will be responsible for management of Joint Endeavor Agreements (JEAs) the Centers for Commercial Development of Space (CCDSs), and the outreach program. In addition to its ongoing program, MSAD will provide scientific support to OCP and will be responsible for all Commercial R&D Enhancement Activities which include commercially oriented research activities, requirements definition studies, and the development of generic facility class hardware for use by commercial as well as academic researchers.

The other recommendations of the Task Force are addressed elsewhere in this report under specific topics.

IV.

REVIEW OF THE MICROGRAVITY SCIENCE AND APPLICATIONS FLIGHT PROGRAMS

In considering the limited number of flight opportunities for microgravity research that were likely to be available in the post-Challenger era until Space Station becomes operational, it became clear that it was necessary to optimize such opportunities by reassessing the scientific goals of the accepted flight experiments, determining and clarifying what hypothesis was being tested, and establishing relative priorities for the experiments. Such prioritization is a first step in making room for new flight experiments to enter the program.

To assist in this task, Dr. J. Robert Schrieffer was asked to serve as chairman of a review committee to evaluate the flight program and to make recommendations to the Director of MSAD with regard to the quality of the research and to point out improvements that could be made in some of the experiments. The membership of the committee was selected by Schrieffer and consisted of an expert from each of the disciplines involved.

The Committee reviewed 49 experiments. The Principal Investigator for each experiment submitted a written description of the experiment along with pertinent publications and made an oral presentation of past work to the Committee. The Committee's evaluations and recommendations were documented in a report entitled, *Review of Microgravity Science and Applications Flight Programs: January–March 1987*. The report, edited by the Universities Space Research Association (USRA), was submitted to MSAD in October 1987.

The Committee pointed out that research in microgravity science and applications is rather different in character from research in those areas in which aspects of space itself are studied. The importance of the ground-based activities to the program was emphasized along with the fact that topics being studied were fast-paced, so that the value of flight experiments depends critically on the availability of timely and frequent flight opportunities.

The Committee agreed that the quality of the program was somewhat variable and the experiments reviewed could be categorized into three groups or levels. The top group represents world class science comparable to the best in the field. These are primarily experiments which are designed to challenge or critically test fundamental concepts or theories having wide impact on science and technology.

The middle group represents focused experiments designed to establish information concerning an important process or property of a specific class of materials.

Those experiments in the lowest group show little promise or few of the features of the above projects. Some of these projects have been supported for many years, have encountered difficulties, and have not maintained the focus of their original goals. In other cases, investigations have greatly broadened their research, incorporating current fashions in the field, thereby distracting them from their original objectives toward unproductive goals.

While dubious about the feasibility of large scale manufacturing in space in the foreseeable future, the Committee viewed the following two concepts as realistic and potentially of great significance:

- Critical experiments designed to guide and accelerate ground based research toward a specific goal. For example, in glass technology, the possibility of reducing critical cooling rates in a microgravity environment may allow one to obtain benchmark materials that may be utilized to more effectively select which of competing future earth-based materials studies and technologies will have greater likelihood of success.
- Development of realistic space based techniques for producing highly specialized materials of great value. An example is one-of-a-kind products such as crystals of biological materials to be used in establishing their molecular structure by x-ray diffraction for pharmaceutical purposes. Another example might be special-purpose semiconductor crystals that are presently impossible to grow on Earth, yet are of great value.

The Committee expressed concern that the limited flight opportunities would make it difficult to attract and retain high-quality scientists who, in a field as vigorous as materials science, cannot afford long delays in getting results. Several of the investigators in the flight program have been overtaken by alternative technologies while awaiting their first flight opportunity. The Committee also pointed out that the potential for research advances of value to industry have made microgravity science a competitive arena on an international scale.

Finally, the Committee recommended criteria for establishing flight priorities, emphasized the need for investigators to formulate clearly the questions to be answered in microgravity experimentation, encouraged more work in analytical and computational modeling of the experiments, and pointed out the necessity of measuring the residual acceleration in synchronization with experiment observation.

MSAD's Chief Scientist has personally contacted each of the Principal Investigators whose experiments were placed in the third category. Several of these investigators have decided to withdraw from the program. Others agreed that they need additional ground-based work before they are ready to utilize a flight opportunity effectively and have subsequently been removed from flight status. The remainder have initiated plans to upgrade their experiment by addressing the weaknesses found by the Committee. In some cases, MSAD has suggested teaming with other investigators or provided additional support to obtain the critical skills needed. These experiments will be reviewed again before flight to assure that deficiencies have been remedied.

V.

RESEARCH PROGRAM OVERVIEW

The Microgravity Science and Applications Division's research program emphasizes three areas: fundamental sciences, material science, and biotechnology. Although Shuttle experiments have not been conducted since 1986, NASA continued an active research program by utilizing ground-based facilities. This chapter presents an overview of the various activities taking place in these three research areas and presents a detailed description of the individual, NASA-sponsored experiments.

FUNDAMENTAL SCIENCES

Fundamental Sciences research includes the behavior of fluids and the study of transport phenomena in microgravity, as well as experiments that make use of the enhanced measurement precision possible in microgravity to measure physical properties and to challenge contemporary theories of relativity and condensed matter physics.

Relativity

A fundamental assumption in Einstein's Theory of Relativity is the equivalence of gravitational and inertial mass. A consequence of this assumption is that all objects should fall at the same rate in a gravitational field. This was demonstrated to first order by Galileo and later by Eotvos to a precision of 1 part in 10^8. More recent work by Dicke and his colleagues has demonstrated this equivalence to a precision of 3 parts in 10^{11}. Despite this precision there are some theoretical and experimental arguments for the existence of a new fundamental intermediate-range force coupled to atomic number. If such a force does exist, there must be a violation of equivalence at some level.

Everitt and Worden of Stanford University have devised an ingenious experiment that has the possibility of extending the precision of such measurements to one part in 10^{17}. Two concentric bodies, a rod and a cylinder of different materials, are placed in Earth orbit and suspended by a frictionless superconducting bearing. Instead of falling the 179 ft. from the Leaning Tower of Pisa, as was the case in Galileo's experiment, these test masses will fall continuously around the Earth. Any violation of equivalence will cause a periodic oscillation, which can be sensed with great precision using superconducting quantum interference devices (SQUIDs).

Work is progressing on development of the superconducting bearing system and the related instrumentation needed to detect the miniscule oscillations. Working to the precision required to achieve the necessary accuracy is a formidable task, but the technologies developed to perform such an experiment may have important applications in other fields such as inertial navigation and guidance systems.

If approved, the experiment could be tested first on the Shuttle or Spacelab to demonstrate the principle and to determine if any unforeseen problems become apparent. These first experiments can provide some three orders of magnitude improvement over Earth-based measurements. Eventually, the experiment may be flown in a drag-free satellite to achieve its ultimate accuracy.

Condensed Matter Physics

There has been renewed interest in recent years in the behavior of condensed matter near the critical point. The critical point is the thermodynamic state of highest temperature at which two phases (e.g., liquid-vapor in a single component system or two immiscible liquids in the case of a binary system) can coexist. Unlike the simple melting of ice, fluids near the critical point have very anomalous properties. For example, large density fluctuations develop as if the fluid cannot decide to be a vapor or a liquid. These fluctuations cause an initially clear fluid to suddenly become turbid. The compressibility becomes infinite meaning that an infinitesimal change in pressure will cause a very large change in volume. In addition, the thermal conductivity and viscosity become infinite while the velocity of sound goes to zero.

A number of practical applications for supercritical fluids are being discovered. Supercritical carbon dioxide (CO_2), for example, is an excellent solvent for organic materials which readily separate from subcritical CO_2. By cycling the temperature or pressure above and below the critical point, an efficient recycling extraction system can be realized. Such techniques are being developed for applications ranging from oil recovery to extracting caffeine from coffee beans.

The theoretical understanding of the behavior of condensed matter during a critical or second-order phase transition was developed by Wilson who applied the renormalization group technique, originally developed for elementary particle theory, to this problem for which he was awarded the Nobel Prize in 1982. Wilson's theory predicts a universal behavior of all matter as the critical point is approached and determines the rate at which the various physical properties become discontinuous.

There are numerous other examples of second-order phase transitions that are important technically. These include spinodal decomposition which is important in alloy solidification, paramagnetic to ferromagnetic transition in solids, and the transition from normal to superfluid behavior in liquid helium. Since Wilson's theory is universal in nature, or independent of the type of atoms or molecules involved, it should apply equally to all such transitions.

Physicists are naturally eager to test such an elegant theory to see if it really does describe the way nature behaves, or if there are other more subtle effects that need to be considered. Discovery of such departures from theory has led us to new and exciting fields in physics. Normally, gravitational forces make a negligible contribution to the chemical potential, which includes the much more powerful electrical intermolecular forces that hold matter together. However, it so happens that at a critical point, all the terms that describe how the chemical potential changes with respect to some order parameter exactly cancel each other and the relatively weak gravity term can tip the balance. This means that in Earth's gravity, critical conditions can only be realized at one specific point along the vertical in an apparatus.

Since the compressibility becomes infinite, the fluid literally collapses under its own weight at this point. Test cells can be made very thin to minimize this hydrostatic effect, but the correlation length (the distance over which density fluctuations occur) becomes long near the critical point and wall effects will interfere. Furthermore, gravitational sedimentation causes phase separation as density fluctuations begin. These difficulties have prevented a definitive test of Wilson's theory of the universality of condensed matter behavior near critical phase transitions.

The participants at the 5th Oregon Conference on Liquid Helium, which included the top low temperature physicists in the world, unanimously supported the statement that microgravity helium physics is a new frontier of science that will flourish somewhere in the world and that it is important to the scientific strength of the United States to contribute to its development.

At Stanford University, Lipa is developing a space experiment designed to measure the heat capacity of liquid helium as it nears the lambda transition between ordinary helium and superfluid helium at 2.17 degrees Kelvin. Because a plot of the heat capacity versus temperature resembles the Greek letter lambda, this transition is referred to as the lambda transition. In the course of this investigation, a novel temperature measurement technique using SQUID detectors was developed that can resolve a temperature difference of less than a billionth of a degree (10^{-9}K) and theoretically can be extended to 10^{-11}K. For the reasons stated previously, the Earth's gravity limits the measurement of heat capacity to within 5×10^{-8} degrees Kelvin of the critical point; in microgravity, measurements could be made to within 10^{-11}K of the critical point. Near the limit of the ground-based measurements, the measured heat capacity departs significantly from the theory. The Spaceflight experiment will determine whether this observed departure is real or an artifact introduced by the slight variation in hydrostatic pressure.

The protoflight hardware has been developed to utilize the Spacelab-2 liquid helium dewar and is undergoing qualification tests at the Jet Propulsion Laboratory (JPL). The experiment will be ready to fly in 1990 on the MSL in the Shuttle payload bay.

Two other experiments are being developed to investigate other features of critical point behavior. Gammon of the University of Maryland will measure the optical scattering in xenon as it approaches the critical point. From such measurements, the correlation length can be determined without the effect of gravity-driven phase separation. This experiment has progressed beyond the conceptual design review, and is being developed for flight on the MSL in 1992.

The second experiment being developed by Moldover and Berg at the National Bureau of Standards (NBS) will measure the viscosity of xenon as it approached the critical point. This experiment is still in the definition phase and is in the process of examining a suitable technique for measuring viscosity in microgravity. Work is progressing on a cup type of viscometer that contains the fluid sample within a cylindrical container that also acts as the inertial element of a torsion oscillator. The damping of the oscillator is used to measure the viscosity.

Fluid and Transport

The vast reduction in density-driven convection provided by the microgravity environment allows the study of other forms of convection such as flows driven by electrodynamics, surface tension gradients, or other interfacial phenomena. Not only are such flows interesting in their own right, but they must be understood and controlled in space experiments. Transport is vastly simplified in the absence of convective flows. This allows many processes involving heat or mass flow to be analyzed and the relative contributions from diffusion and convection sorted out.

An elaborate experiment to study the flows caused by surface tension gradients is being developed by Ostrach and Kamotani at Case Western Reserve University. A cylindrical container 10cm diameter by 5cm deep filled with silicone oil is heated on its free surface using either a laser or an immersible heater. Since surface tension is lowered by increasing temperature, unbalanced surface forces will result and will drive flows in the fluid. A cross section of the container is illuminated by a sheet of light and the flow field is mapped using marker particles. The temperature field on the free surface is mapped using an imaging infrared radiometer. The physical properties of the fluid have been carefully measured, thus the resulting flows can be precisely compared against computer models. Considerable attention has been given to controlling the contact angle between the fluid and the container wall, which determines the shape of the free surface in the absence of gravity.

Although the primary purpose of the experiment is fundamental in nature, the configuration is similar to that used in the Czochralski method of crystal growth, which is widely used for the industrial production of silicon and gallium arsenide crystals for semiconductor applications. Understanding how to model the surface tension components of the flows may provide insight for controlling convection in such processes. Of particular interest is the conditions under which such flows undergo a transition from steady laminar convection to unsteady or turbulent flows that are believed to cause growth rate fluctuations, striations, and other defects in the grown crystals.

This experiment has successfully completed the Preliminary Requirements Review and the flight hardware is being developed for flight in the USML-1.

At Rensselaer Polytechnic Institute (RPI), Glicksman is developing an elegant experiment to study the growth of dendrites as a material solidifies into a slightly undercooled melt. It can be shown that a plane solidification front in molten metals will be unstable if it advances into a melt that is even slightly below the local freezing temperature, which is usually the case in casting, welding, and other solidification processes. The solid then forms with a dendritic or tree-like structure. The dendrite arms or branches produce the microstructure that affect the mechanical properties of the solid; therefore, there is great interest in understanding how dendrites form and how their growth can be controlled.

A theory to predict the growth rate and shape of dendrites under diffusion controlled conditions that can only be realized in microgravity has been developed; however, having to account for the addition of convective effects would make the theory intractable . A low melting temperature, transparent material, succinonitrile, has been selected because, like most metals, it has a low entropy of fusion, which allows it to solidify dendritically instead of forming facets. All of its relevant properties have been carefully measured, including the liquid-solid interfacial energy, which is needed for comparison with theory.

The experiment has successfully passed Conceptual Design Review and Preliminary Requirements Review. A precision thermostatted chamber has been developed that can maintain temperatures to within 0.002 Kelvin. Techniques for measurement of dendrite tip radii down to 20 microns have been demonstrated and improvements are planned to permit measurement to 10 microns (a needle point has a radius of 25 microns). The Critical Design Review was held in April 1988 and the experiment will be available for flight on the MSL in 1990.

An experiment to investigate nucleate pool boiling in microgravity has been initiated by Merte of the University of Michigan. Heat transfer during various types of boiling is a complex but very important process on Earth and will become increasingly important in space as techniques for removing or transferring large heat loads that will work in microgravity are required. A portable experiment apparatus has been developed for measuring heat transfer and bubble growth/collapse in Freon 113 heated by a thin gold foil heater. This allows experiments in both normal and inverted gravity as well as in the 5 second droptube at Lewis Research Center (LeRC). This experiment has just completed Conceptual Design Review and will be available to fly in a Get-Away Special (GAS) container in 1991.

Wang and his team have been using the drop tubes at JPL to study the formation of spherical shells. Initially, this effort was aimed at studying the mechanism by which bubbles in liquid drops become centered with the aim of producing highly concentric spherical shells for inertially confined fusion experiments. Techniques were developed for forming such shells from glass, metals, and plastics by extruding the molten material through an annular jet and allowing the Rayleigh instability in the column of liquid to form the spherical shells which then solidify as they continue to fall.

A number of applications have been found for such shells. For example, they can be sintered or otherwise bonded together to form an extremely rigid, light weight structure (syntactic foam) with excellent energy absorbing characteristics. Techniques are being developed to form small polymeric shells around living cells that will allow the passage of low molecular weight proteins, such as insulin, while preventing the passage of larger-molecular weight antibodies that could attack the cells. Such cell encapsulation techniques could be extremely important in the treatment of diseases such as diabetes.

These activities began under the auspices of the microgravity program as potential flight experiments. As is often the case, such research leads to totally different results than was originally anticipated and applications are discovered that do not require microgravity. When such research becomes sufficiently mature, it is phased out of the microgravity program through the NASA's Technology Utilization Office so that it can be picked up by private companies or by other government agencies.

Combustion Science

Because combustion processes involve the release of chemical energy, which results in steep thermal gradients, buoyancy driven convection plays a major role in transport of heat and chemical species at unit gravity. Microgravity significantly reduces this convective transport which enables researchers to study the combustion process under vastly simplified conditions. In addition to obtaining fundamental knowledge, there is also the practical aspect of spacecraft fire safety and how to deal with a potential fire.

A solid surface combustion experiment has been developed by Altenkirch at the University of Kentucky. Various samples of paper and plastic sheets will be ignited in a special containment chamber and the flame shape and propagation rates will be recorded by cinematography. A number of tests of the apparatus have been conducted in the two-second droptower and the five-second droptube at LeRC and in the KC-135 aircraft. These tests, in addition to verifying the operation of the system in microgravity, have provided valuable scientific return, but the limited duration does not allow the combustion process to reach equilibrium. Flight hardware has been developed, qualified, and placed in storage awaiting a middeck flight opportunity on the Shuttle.

At Princeton University, Williams and Dryer have developed a droplet combustion experiment. A droplet of fuel is freely suspended and ignited with an electrical spark. The droplets are large enough to permit accurate measurements of the droplet and flame diameter which can be compared to analytical models to develop scaling laws that apply to microscopic droplets in spray burning, diesel engine combustion, and other important processes on Earth. A test apparatus that utilizes the five-second droptower at LeRC has been used to develop the deployment and ignition system as well as to get important scientific return. One difficulty has been the limited time for the damping of the oscillation induced in the droplet during the deployment which confuses the analysis. The observation of soot forming on the surface of the droplet which results in self-disrupting or explosion of the droplets was an unexpected result. Several other issues identified at the Preliminary Design Review remain to be resolved before the project is brought to Critical Design Review. However, it is expected that a droplet combustion experimental module will be tested during the USML series as an element of the Modular Combustion Facility to be flown during the Space Station Era.

An experiment to gain a better fundamental understanding of the effects of buoyancy on laminar jet diffusion flames was developed by Edelman and Bahadori of the Science Applications International Corporation. Following the Conceptual Design Review, it became apparent that most, if not all, of the experiment objectives could be accomplished in the times available in the LeRC droptower or on the KC-135 aircraft. Therefore, the experiment has been continued in these suborbital facilities. Preliminary results in the 2.2 second drop facility at LeRC obtained good quantitative results, which are being collated with computational models that describe the important mechanisms of such flames.

Berlad of the University of California San Diego (UCSD) is investigating particle cloud combustion such as that involved in dust explosions in coal mines or in grain storage buildings. The experiment requires the deployment of a uniform particle cloud that will remain suspended in a long tube for a sufficient time to characterize the cloud and measure the propagation of a flame through the tube. Microgravity would greatly aid this suspension. However, it has proven more difficult than anticipated to deploy a uniform suspension of ultrafine particles because of charging effects that cause the particles to stick to the walls. Use of a small amount of polonium 210 isotope to produce ionizing radiation that would bleed off the charge is being considered. Approval for the development of this experiment for space flight is being withheld until this problem is resolved.

MATERIALS SCIENCE

Research in materials science includes the processing of electronic and photonic materials; metals, alloys, and composites; glasses and ceramics; and polymers. The primary objective of this research is to obtain a better understanding of the role of gravity-driven convection in the processing of such materials with the goal of effecting better control strategies on Earth.

Just as the development of more precise temperature control has greatly enhanced our ability to improve the properties of materials, the ability to control convective transport during processing should provide even more dramatic improvements in properties. From these experiments, new processing technologies should evolve that take full advantage of the microgravity environment. Production of limited quantities of exotic new materials with superior properties that can serve as benchmarks or for certain strategic applications should be posssible. Eventually, such efforts could lead to commercially viable enterprises.

Materials scientists desire to understand the formation, structure, and properties of materials at the atomic and molecular level. This understanding includes the relationship between the microstructure of the material and its physical properties as well as how to achieve a given microstructure by manipulating the various processing parameters. The formation of many, if not most, materials important to modern technology involves solidification from a fluid state.

Since it is often desirable to mix two or more components to obtain compounds, alloys, or composites with improved physical properties, the solidification process is complicated by the fact that different atoms do not generally enter the solid in the same proportion as they are in the melt or vapor. This segregation produces local variations in composition in the fluid phase which in turn changes the temperature at which portions of the solid will form.

The situation is further complicated by the presence of convective flows which further alter the local composition and the temperature of the fluid. As the understanding of these processes has increased, the processing of materials has evolved from an empirical to a more exact science and considerable progress has been made in understanding some of the simpler systems from first principles. A key to this progress has been the improved ability to control the solidification process which has come about through a better understanding of the interrelationships between the fluid phase and the solidification interface.

The microgravity environment provided by an orbiting spacecraft offers a new dimension in the control of the solidification process. Convective flows can be drastically reduced, which permits a more precise control of the temperature and composition of the fluid and vastly simplifies the analysis. Body force effects such as sedimentation, hydrostatic pressure, and deformation are similarly reduced. As an additional benefit, non-contacting forces such as acoustic, electromagnetic, or electrostatic fields can be used to position specimens while they are being processed, thus avoiding contamination of reactive melts.

As a result of their review of the Microgravity Program, the Schrieffer Committee reconfirmed the need for an instrument to measure and correlate residual acceleration in real time. The Space Acceleration Monitoring System (SAMS) is a general purpose system being developed to measure and record these data.

Electronic and Photonic Materials

Exciting new electronics and photonics (combination of optical and electronic components) advances in recent years have become possible because of our increased ability to engineer the structure of materials at the molecular level. The development of solid state electronics was enabled by our ability to produce very pure single crystalline solids from Group IV elements in the periodic table (primarily silicon and germanium) that have semiconducting properties, and on the ability to introduce precisely controlled trace quantities of dopants that significantly alter the electrical properties.

This is now a mature technology because of our increased ability to control the solidification process. Some of the early microgravity experiments on Skylab and Apollo-Soyuz played a part by calling attention to the role of gravity in transport during the solidification. These early experiments helped stimulate a productive interdisciplinary approach between fluid mechancians and crystal growers to the design of crystal growth processes.

Strong magnetic fields are now used (especially in Japan) to eliminate turbulent convective flows in large melts; however, this approach is only effective in conductive melts and not even the strongest magnetic fields can reduce buoyancy-driven convective flows sufficiently to achieve diffusive transport in earth's gravity. In fact, studies indicate that it will be difficult to achieve diffusion control in a large-scale process even under microgravity conditions unless magnetic fields are also applied to help suppress the convective flows driven by the residual accelerations and other non-gravitational effects.

The strategy is to first investigate the advantages of growing crystals under diffusion controlled conditions, which can be accomplished in microgravity for size scales on the order of a few centimeters, and from this determine the necessity and the most effective approach for scaling up the process.

As mentioned previously, device technology based on elemental semiconductors (primarily silicon) is mature and is approaching the theoretical limit. This is not the case for some of the newer materials based or Group III and Group V compounds (e.g. gallium arsenide, indium phosphide) or Group II and Group VI compounds (e.g. cadmium telluride) or various alloys of these elements (e.g. mercury cadmium telluride, gallium indium phosphide, etc.).

Such materials have unique properties that cannot be obtained from elemental semiconductors. For example, some have direct bandgaps, which means that they can convert electrical energy directly to light and vice versa. They also have higher electron mobilities which means they can switch or process information faster. In addition, they have more tolerance to hostile thermal and radiation environments. Because of these properties there is intense interest in this research from both the military as well as the advanced civilian electronics community.

Despite this interest and the large amount of research that has been devoted to the development of such materials, many problems remain which have limited their applications. The presence of multiple components adds another dimension of control that is required on the stoichiometry or composition of the material. The crystalline lattice of many such materials tends to be soft, especially near the growth temperature, and it has been difficult to control the formation of various defects that affect device performance. There is even some evidence that large crystals may actually deform under their own weight during solidification. A well-conceived set of experiments in microgravity could elucidate the role of convection in the control of composition and defect formation as well as the role of container walls and hydrostatic pressure in the formation of dislocations.

Wiedemeier of RPI grew crystals of germanium selenide and germanium telluride by chemical vapor transport on Skylab and Apollo-Soyuz, and by physical vapor transport on STS-7 and STS-61A. In general the space experiments produced a greatly improved surface morphology that was virtually free of growth defects whereas the Earth-grown control samples exhibited substantial pitting and irregular growth terraces that presumedly resulted from uncontrolled convective flows. Building on these results with simpler model materials, Wiedemeier is preparing the next set of experiments that will involve materials of technical interest, i.e., mercury cadmium telluride ($Hg_{0.8}Cd_{0.2}Te$).

Techniques have been developed for growing reproducible epilayers of HgCdTe on cadmium telluride (CdTe) substrates using mercuric iodide (HgI_2) as a chemical vapor transport agent. The use of a chemical transport agent allows a lower growth temperature which reduces defect formation and interdiffusion into the substrate. The experiment is designed to be flown in the Chemical Vapor Transport Furnace being developed by Boeing under a JEA as well as in the USML Crystal Growth Furnace.

An important by-product of this work was the first direct measurement of the Hg-vacancy concentration in $Hg_{0.8}Cd_{0.2}Te$ employing dynamic microbalance techniques from which the heat of formation of Hg-vacancies was derived. This information is valuable in understanding and being able to control such defects in the crystal growth process.

Van Den Berg of EG & G Corporation successfully grew mercuric iodide by physical vapor transport on Spacelab-3. This is a very useful material for gamma-ray detectors, but has always been difficult to work with because of its very weak crystalline lattice. In fact, it has been suspected that one of the limiting factors in its performance has been deformation under its own weight during the growth process.

The initial characterization results of the space-grown material were very encouraging. Gamma-ray rocking curve data revealed only single peaks throughout the entire crystal which indicates a very high degree of internal order. Multiple peaks are usually observed in material grown on Earth, which indicate the presence of multiple crystals with low-angle grain boundaries. The first measurements indicated mobilities of both electrons and holes that were at least a factor of 2 higher that the best crystals grown on Earth. The product of hole mobility and lifetime, which determines the efficiency of a detector, was higher than the best Earth-grown crystal by a factor of 7. Subsequent measurements of electron and hole mobilities no longer repeat the earlier measurements, but are now comparable to the best Earth-grown crystals.

Although this discovery is very intriguing, there is always the possibility that the first mobility measurements were in error, even though they were repeated by different groups. After the fabrication and evaluation of the detectors, other measurements on the materials were planned. To do those measurements, the detector was not covered with a protective coating as is normally done. In the past, degradation of detector performance has been observed in uncoated detectors, and it is believed that this is the reason for the degradation in the space-grown detector.

A reflight of the experiment is planned for the first IML mission in 1991. This reflight will determine if the dramatic improvement in performance apparently achieved in the crystal grown on Spacelab-3 can be reproduced. If so, a significant case can be made for growing such crystals in microgravity.

Crouch and Fripp of Langley Research Center (LaRC) attempted an experiment on STS-61A to determine the amount of residual convection in a thermosolutally unstable, compound semiconductor material in a low-gravity environment. Through a post-flight measurement of the macrosegragation in a space-grown crystal of lead tin telluride (PbSnTe), a qualitative assessment could be made as to how close the growth conditions were to a diffusion controlled situation.

Since the only furnace available at the time was the general purpose furnace derived from the SPAR rocket progam, it was recognized that the interface shape could not be controlled and that quantitative answers could not be obtained. However, due to a malfunction in the hardware during the flight, the furnace did not operate as planned and the growth rate was not constant.

Post-flight analysis indicated that convection dominated the mass transport, and etching studies implied that the flow was probably oscillatory. With the limited accelerometer data available, nothing definitive can be said about the cause of this mixing. However, this experiment proved the importance of careful furnace design and the strict temperature control required to grow high-quality crystals in space. Follow-on experiments of this type will utilize the Advanced Automated Directional Solidification Furnace (AADSF) on the MSL or the Crystal Growth Furnace in the USML series, which have much greater control of the interface temperatures and growth rates.

This particular system is subject to a double convective instability because a less dense, tin-rich solute is rejected at the growth interface which is solutally unstable and tends to rise in Earth's gravity in normal growth conditions. Inverting the furnace would place a hotter, less dense bulk melt below the cooler melt near the growth interface which is thermally unstable. This situation makes achievement of diffusion controlled solidification on Earth impossible and very difficult even under microgravity conditions.

Development of a flight experiment to investigate the possibility of growing homogeneous bulk crystals of mercury cadmium telluride (HgCdTe) is continuing at MSFC by Lehoczky and Szofran. This is a crucially important material for infrared detectors and thermal imaging arrays. Unlike, the PbSnTe system discussed previously, this system rejects a higher-density, Hg-rich solute at the growth interface and is, therefore, solutally and thermally stable. Diffusion controlled growth can be obtained along the axis of the growth furnace because of this stability, but it has been virtually impossible to achieve radial homogeneity because of the tendency of the dense Hg-rich diffusion layer to flow to the lowest point of even a slightly curved solidification interface. Since, the bandgap, hence the spectral response of a long-wave length infrared detector depends greatly on the composition, such inhomogeneities cause difficulties is preparing imaging arrays from bulk materials.

Considerable progress has been made at MSFC in understanding the gravitational limitations in the growth of bulk semiconductor materials such as HgCdTe. This experience is being carried over to investigate mercury zinc telluride (HgZnTe) and mercury zinc selenide (HgZnSe), which have optoelectronic properties similar to HgCdTe, but the substitution of zinc appears to stabilize the crystalline lattice, and may have the potential to lower the defect density of the grown crystals.

There is also major interest in the growth of the simpler compound CdTe, which is needed for use as a substrate material on which HgCdTe can be grown by liquid or vapor phase epitaxy in order to avoid the compositional homogeneity problem described previously. Defects such as dislocations, grain boundaries, and twinning have been serious problems in the growth of CdTe. Microgravity experiments may provide insight on methods for controlling such defects. MSFC is developing such an experiment in conjunction with Rockwell Science Center. These experiments can be carried out in the AADSF on the MSL or in the Crystal Growth Furnace being developed for the USML.

MSFC is also working with the U.S. Army Missile Command (MICOM) and Rosenberger, University of Alabama in Huntsville (UAH) to investigate ways of improving the growth of cadmium sulfide (CdS) needed for ultraviolet detection and imaging. A flight experiment is being developed to use the Boeing Chemical Vapor Transport Furnace as NASA's part of the quid pro quo in the JEA between Boeing and NASA.

A joint NASA, Air Force, and GTE funded experiment is being developed by Kafalas of GTE to compare the growth of gallium arsenide (GaAs) in space against growth under different orientations on Earth with the objective of relating convective effects to macro and microsegregation (inhomogeneties on a bulk and microscopic scale). In addition, the ground-based experiments have been conducted with and without a strong magnetic field to provide direct comparison of the effectiveness of microgravity versus magnetic damping for suppressing convective effects. It has been demonstrated that striations can be eliminated and dislocation densities lowered by application of the magnetic field to stabilize the growth rate and eliminate time dependent flows.

The experiment is self-contained and designed to fly in a GAS cannister. This appears to be a reasonable first step if an early flight opportunity presents itself, but there is concern that the simple gradient freeze furnace cannot produce a high-quality crystal in space. Consideration is being given to repeating this experiment in the Crystal Growth Furnace on USML.

Another important class of materials that is emerging for optoelectronic and photonic applications are various organic and polymeric crystals. The non-centrosymmetric space group of certain organic and polymeric crystals can produce strong non-linear optical behavior which is required for applications such as optical modulators, frequency doublers, optical switching and logic circuits, and ultimately optical computing which promises to be orders of magnitude faster than convectional electronic computing. Advances in this field are presently limited by the availability of suitable materials in crystalline form. Thin films of organized monomers can be grown by the Langmuir-Blodgett technique but achieving bulk materials has proven difficult.

The 3M Corporation has a major interest in the problem of self-ordering molecular systems and how to produce them. This has been the thrust of their JEA activity with NASA. To date, 3M has flown 3 experiments in their own organic crystal growth apparatus. Two such experiments involved growth from solution and the third experiment involved growth from vapor. The vapor growth experiment yielded by far the most interesting results, which are still carefully being analyzed. While it is still too early to make a definitive statement, some of the space grown organic films appear to be substantially different, both optically and morphologically, from their ground-control counterparts. It is difficult to understand from conventional fluid mechanics how gravity effects could be important in a physical vapor deposition process over the scale involved in thin film deposition, but if this is actually true, it could have a profound impact on our knowledge of microscale fluid effects that operate near an interface.

Metals and Alloys

Most of the metals and alloys used today are cast from the melt. The solidification in a casting process is even more complex then the growth of single crystals, though not as well controlled. Useful alloys often have multiple components each of which has a different freezing temperature. In addition to the segregation effects described in the previous section, multiphase reactions can occur when a liquid transforms into two distinct solids (eutectic reaction), into a solid and a second liquid (peritectic reaction), or into two immiscible liquids (monotectic reaction). Invariably these multiple phases have different densities which cause macrosegregation (variations in compositions over the bulk). Some of the earlier microgravity experiments revealed the influence of strong interfacial effects which also play a major role in phase separation.

In most cases it is neither feasible nor even desirable to provide the large thermal gradients needed to stabilize a planar growth interface and, as a result, dendrites form. The interdendritic fluid has a different composition and freezing point from the bulk melt. The interplay of dendrites and the interdendritic fluid in the region called the mushy zone, determine the microstructure which is responsible for the physical properties of the solid. Convective flows in the mushy zone can cause dendrite arms to break off and be carried to other parts of the casting where they nucleate other grains. In large castings, the inherent slow cooling allows the individual grains to grow by a process called ripening which is driven by nature's attempt to minimize the chemical potential by reducing the interfacial energy.

Historically, most metallurgical processes evolved by trial and error. Given the virtually infinite combination of processing parameters that can be varied, progress can be made only by developing insight and guiding principles. Microgravity offers the possibility of isolating certain transport mechanisms in order to study their effect and to determine if and how they should be controlled.

One technique for studying the complex processes that occur during alloy solidification is to use simple transparent model systems that are analogous to the process of interest. A number of systems have been accurately modeled. This effort can be generalized to a variety of practical applications.

Hellawell of Michigan Tech is using ammonium chloride (NH_4Cl) and water to study the formation of channels of low-density materials during the solidification of a casting that produces defects known as freckling. The NH_4Cl-H_20 solution rejects a water-rich phase during solidification, which is less dense than the bulk fluid, and, like many alloy systems, makes it subject to unstable solutal convection. The central issue is whether the columns responsible for freckle formation originate in the mushy zone or in the unstable region of rejected low-density melt just ahead of the mushy zone. This understanding is crucial to developing strategies for controlling such effects.

A space experiment using the same transparent analog system is being developed by McCay and McCay at the University of Tennessee Space Institute (UTSI). The emphasis of the experiment is to determine the extent and stability of the low-density region just ahead of the mushy zone. A stability analysis by Coriell (NBS) several years ago indicated that such systems were highly unstable even under greatly reduced gravity levels. Coriell's analysis was for a plane solidification front of infinite extent and did not consider the effect of a mushy zone or of the walls of a container which tends to stabilize the system against convection. The flight experiment will use the holographic optical system in the Fluid Experiment System (FES) on IML-1 to map the compositional profiles of the melt under different growth conditions and to determine the region of stability.

One technique for controlling the microstructure during the solidification of an alloy is to extract the heat unidirectionally (directional solidification). This is similar to the Bridgman technique for growing single crystals except that the thermal gradient may not be sufficient to prevent dendritic growth at the interface. With directional solidification, it is possible to produce aligned microstructures which give rise to highly-anisotropic properties such as increased strength, resistance to creep, enhanced magnetic strength, and other interesting electrical properties. Eutectics, in which a homogeneous melt forms two nearly immiscible solids upon freezing, can produce unusual microstructures consisting of continuous rods or lamella of one solid phase in a matrix of the second solid phase.

The theory of eutectic formation, developed in a classical paper by Jackson and Hunt, argues that mass transport responsible for the phase separation is diffusion controlled and predicts that the spacing between rods should be inversely proportional to the inverse square of the solidification velocity.

Larson of Grumman Aerospace Corporation directionally solidified a manganese-bismuth (MnBi) eutectic during the Apollo-Soyuz mission and found greatly enhanced magnetic properties in the flight sample. It was later discovered that the rods of MnBi compound, which form the magnetic phase in the bismuth matrix, were finer and more closely spaced than in the ground-control sample and fortuitously were nearly the optimal size to have magnetic properties close to the theoretical limit.

Subsequent experiments on SPAR rockets at different solidification rates showed significant departures from the Jackson and Hunt theory, which were also found in ground-based experiments using strong magnetic fields to suppress convection. German and French experiments on Spacelab-1 and SL-D1 (first German Spacelab) also found departures from the theory with different material systems. The interesting fact is that the theory, which assumes no convection, appears to agree with experiments when convection is present, but breaks down when convection is suppressed. Apparently, eutetic phase formation is more complex than originally imagined. .

A novel technique for using the KC-135 aircraft for low-gravity research in metals and alloys has been developed by Curreri at MSFC. An ingot is directionally solidified by slowly withdrawing it from a furnace while the aircraft flies its series of ballistic parabolas that produce 20-30 seconds of reduced gravity interspersed with 1-2 minutes of increase gravity from the aircraft pull-out maneuver. The resulting solid then contains alternating bands of material solidified in high- and low-gravity for direct comparison. Admittedly, there are many shortcomings to the technique. The times available do not permit equilibrium to be reached; the bulk melt is stirred by buoyancy-driven convection after each parabola; and the amount of material solidified in low-gravity is not sufficient for evaluation of mechanical properties. However, some very interesting results have been obtained which will stimulate more precisely controlled experiments when Shuttle flights resume.

A study of iron-carbon alloys, conducted under a Technical Exchange Agreement with John Deere, has shown that microgravity effectively decreases buoyancy-driven graphite phase segregation. Therefore, the growth of metal-graphite composite materials with unique electronic and structural applications might be possible in space. These studies have been extended to iron-carbon-vanadium alloys. The results show that although most of the vanadium carbide segregation is buoyancy driven, some of the segregation is due to another mechanism, probably particle/solidification interface interactions.

Studies of superalloys were continued by Principal Investigator J. Lee of the MSFC's Materials and Processes Laboratory. Past studies with superalloys have demonstrated the effect of gravity level during solidification on dendrite spacing for a superalloy used in the Shuttle main engines (MAR-M246) and on a single crystal superalloy (PWA-1480). In order to test the hypothesis that buoyancy-dependent segregation of solute is causing the gravity dependence of dendrite spacing, an interface quenching system was developed for the aircraft furnace. Cooling rates of instrumented samples of 100 degrees C per second were achieved, allowing interface quenching in the last half of the low-gravity period. The samples are being analyzed by microprobe to ascertain the compositional profiles in the quenched liquid and dendrite tips.

Studies of ceramic metal matrix materials were initiated under a Technical Exchange Agreement with ABEX Corporation. A new furnace was designed for the ceramic metal composite studies to allow both the melting and solidification of a sample to occur during the same low-gravity period. This approach prevents segregation of the solid ceramic particles between low-gravity intervals. Samples of an aluminum-nickel eutectic with silicon-carbide particles were processed. Surface and buoyancy forces as well as particle incorporation at the solid/liquid interfaces were isolated.

Several early microgravity experiments attempted to obtain alloys from systems that exhibit a liquid miscibility gap; i.e., a range of compositions in which the melt decomposes into two immiscible fluids with different compositions, very much like a mixture of oil and water. Since these two liquids will invariably have different densities, sedimentation produces massive phase separation in unit gravity before solidification could occur. Microgravity seemed an ideal solution for producing a variety of these alloys directly from the melt. Conventional powder metallurgy can, of course, produce such alloys by hot isostatic pressing (HIP), but fine metal powders always have oxide or other adsorbed impurity layers on their surface which tend to prevent an intimate contact between the particles when they are compressed. This intimate contact may provide enhanced mechanical, unique electrical, and possibly even superconductive properties.

Despite an initial success by Reger and Yates, who succeeded in producing a fine dispersion of gallium in bismuth using the MSFC droptower (this result was recently repeated by Wu) a variety of early spaceflight experiments observed massive separation of the two immiscible liquid phases before solidification could occur. Generally, the minority phase would wrap around the majority phase, isolating it from the crucible walls. Also, some of the minority phase would also be found near the center of the ingot which was the last portion to freeze. Clearly there must be strong interfacial forces acting to produce this phase separation that had been previously masked by gravity driven sedimentation.

These interfacial effects are now understood. Cahn, in his classical paper on critical wetting, showed that for monotectic systems which undergo a critical phase transformation in which a single liquid decomposes into two immiscible liquids, there must be some temperature range in which one of the two liquid phases becomes preferentially wetting. If the preferentially wetting phase happens to be the minority phase, which apparently was the case in the early spaceflight experiments, the system becomes unstable and the minority phase will intervene between the majority phase and the crucible wall (or free surface in case of a freely suspended drop).

This situation can be controlled by choosing the crucible material so that it is preferentially wetted by the majority rather the minority phase as was demonstrated by Gelles in his STS-7 experiment. This proper choice apparently was fortuitously made by Reger and Yates in their early droptower experiment. However, the fine dispersions in these samples observed by Lacy and Otto obtained in the 4 seconds available during the droptower test have not been duplicated in the spaceflight experiments using larger samples and longer solidification times. There are apparently a number of ripening or coarsening effects as well as agglomeration effects that must be understood and controlled.

As the melt is cooled into the two-liquid phase region, the minority phase nucleates to form fine droplets. Even in the absence of gravity, these droplets can move because of unbalanced interfacial effects. These arise as heat is extracted because surface tension, or interfacial tension in this case, is a function of both temperature and composition. The combined thermal and compositional gradients drive the small droplets in a direction to reduce the overall surface energy; usually toward the hottest or last-to-freeze region. Larger droplets tend to move faster than smaller droplets, overtaking them and becoming larger still.

Frazier of MSFC has developed neutrally buoyant transparent analogs to study these complex processes in earth gravity. A mixture of succinonitrile and deuterated water form a simple monotectic system that can be made isopychnic (neutrally buoyant) by adjusting the relative amount of deuterated water (D_20) to normal water (H_20). Unfortunately, the thermal expansion of water is different from succinonitrile so that system is only isopycnic at one temperature. Therefore, it is still difficult to perform experiments with large thermal gradients in normal gravity and KC-135 flights are being used to complement this effort.

To aid in these studies it is necessary to have a complete thermodynamic characterization of the system. Systems with liquid phase miscibility gaps depart significantly from ideal solutions as the consolute temperature is approached. Raman and resonance Raman spectroscopic methods are being used by Loo (UAH) to determine cluster formation as a function of temperature. The measurements will be compared to quantum mechanical computations performed by Hall of Atlanta University.

Studies of immiscible alloys were continued by Curreri, Wu (UAH), and Chu (University of Houston). Immiscible aluminum-indium-tin alloys were solidified during aircraft maneuvers and then sectioned to measure the electrical properties of samples of solidified in low and high gravity. The samples solidified in low gravity have superconducting transition temperatures approximately 15% higher than those samples solidified in high or normal gravity. The resistivity characteristics of samples solidified in low gravity are semi-metallic while those of samples solidified at high or normal gravity are metallic.

This same effect had been observed in several previous low-gravity solidification experiments on Skylab and in droptowers. Wu and Chu speculated that the finer dispersion of the immiscible phase that might result from low-gravity solidification could produce a superconduction mechanism based on excitons rather than electron-phonon interactions described by the conventional Bardeen-Cooper-Schrieffer (BCS) theory of superconduction. Much detailed analysis of the microstructures of the material solidified in low-gravity will be required before a definite conclusion can be reached. This work has been postponed, however, following Wu and Chu's discovery of the high temperature superconductor based on the yttrium-barium-copper-oxide (Y-Ba-Cu-O) system which sparked the intense recent interest in new, high-temperature superconductors.

Many alloys of practical interest derive their strength and toughness through dispersion hardening. Submicron refractory particles can be added to a melt or intermetallic phases can be caused to precipitate from the melt as it is cooled to provide the dispersed phase. These dispersed particles block the motion of dislocations as the material is stressed and increase resistance to creep at high temperature. To be effective, such particles must remain small and well dispersed. Although solid particles are not subject to migration driven by interfacially driven flows, as was the case for liquid droplets, there are still other non-gravitational effects that effect both solid particle and liquid droplets. Thermophoresis and particle pushing at a solidification interface are examples of such effects.

Another important effect is coarsening or ripening which causes larger particles, droplets, or dendrites to grow at the expense of the smaller. This effect is described by a classical theory developed by Lifshitz, Slyozov, and Wagner (LSW). The LSW theory, however, uses a mean field approximation and is applicable only when the volume fraction of the dispersed phase is negligible. Corrections to the theory for large volume fractions and nearest neighbor efforts were developed by Glicksman of RPI and Voorhees of Northwestern University. Careful Earth-based tests by Voorhees revealed departures by as much as a factor of two from the corrected theory at large volume fractions. It is possible that this discrepancy may be caused by convective transport which is not taken into account by the theory. A flight experiment to test this assumption is being considered for the Metals and Alloys Solidification Apparatus to be flown in the USML series.

Similar coarsening as well as gravitational settling effects have been found in liquid phase sintering of tungsten alloys by German at RPI. This process is used to form composites with refractory components by binding an aggregate of fine refractory particles in a matrix of lower melting material. German found increased coarsening at the bottom of the sample which contained as much as 93 wt% tungsten in a iron-nickle matrix, indicating a definite gravity influence. A flight experiment is also being considered for the Metals and Alloys Solidification Apparatus in the USML series to determine the coarsening rate in the virtual absence of gravity.

Conductive samples can be levitated and heated by strong electromagnetic fields, thus samples may be melted and solidified without physical contact. This is important for dealing with very high temperature melts which would dissolve any crucible or when extreme purity is required. One limitation of this technique in normal gravity is that it is difficult to decouple the levitation and heating. Also, the levitation forces create turbulent convective stirring in the melt. Finally, there is a point on the levitation axis where the levitation force is zero, hence there is a small hole in the bottom of the electromagnetic "bucket" and surface tension must support the melt at this point. In microgravity the current required to position the sample is dramatically reduced along with the concomitant stirring and heating effects, thus it is believed that substantially greater degrees of undercooling (lowering a melt below the normal freezing point without solidifying) can be achieved.

In order for a melt to solidify, it is first necessary to form a nucleus or cluster of atoms in the solid phase, larger than a critical size, to get over the barrier imposed by the interfacial energy of the system. This is most easily done by the atoms forming on a speck of impurity in the melt, an oxide layer on the surface, or on surface imperfections on a container wall. By eliminating walls and working with highly purified systems, it should be possible to approach the limit of homogeneous nucleation or the degree of undercooling at which the atoms in the melt spontaneously form clusters of the critical size. This limit is not known for most metals. The several conflicting theories for homogeneous nucleation have never been critically tested, and whether or not stirring or other mechanical disturbance affects the nucleation rate, can only be speculated.

Rapid solidification is a new technology that is quickly growing in importance. By quenching a melt so rapidly that the atoms do not have a chance to arrange themselves into their equilibrium or lowest energy configuration, a rich variety of metastable or even amorphous phases can be formed. This is normally done by splat quenching or melt spinning, in which a melt is ejected onto a rapidly rotating chilled wheel, producing a thin ribbon of solid material. Allied-Signal Corporation produces Metglass, an amorphous iron-boron alloy used in transformer cores by this process. The absence of grain boundaries, which would tend to pin the magnetic domains, reduces the hysteresis loss dramatically and can improve the overall efficiency of a transformer. Another technique, called "glazing" uses pulse lasers to quickly melt the surface of metallic alloys. The heat conduction into the bulk solid produces rapid solidification resulting in an amorphous surface which has good corrosion resistance.

A deeply undercooled material will also solidify very rapidly once nucleation occurs, and non-equilibrium or amorphous phases may be produced in bulk quantities by this method. Lee of JPL and Drehman of Harvard University demostrated that for certain metallic glass formers such as Au-Pb-Sb and Pd-Si systems, the amorphous phase can be formed with samples processed through droptubes.

Using the 100-meter droptube at MSFC, Bayuzick of Vanderbilt University and Robinson of MSFC studied the formation of metastable A-15 phases in niobium alloys (Nb-Ge, Nb-Si, and Nb-Pt) which, before the discovery of the Y-Ba-Cu-O system by Wu, had the highest known superconducting transition temperatures. These nonequilibrium phases cannot be formed by normal freezing, but must be formed by melt spinning or vapor codeposition. Some metastable A-15 phase formation was observed in the drops that deeply undercooled while they fell in the drop tube, but it appears that most of this non-equilibrium phase reverted back to equilibrium phases during recalescence (the heating of the sample back to above the freezing temperature when the latent heat of fusion is liberated).

Collings of Battelle's Columbus Division showed that splat quenching after deep undercooling trapped a much higher fraction of the metastable delta-ferrite magnetic phase in austenitic stainless steels than either splat quenching or spontaneous nucleation of an undercooled melt.

Maximum undercooling studies of a number of pure elements (titanium, zirconium, niobium, molybdenum, rhodium, tantalum, and platinum) were also made in the 100-meter droptube. Undercoolings ranging from 17-20% of the melting temperature were observed, which is consistent with the classical theory of homogeneous nucleation developed by Turnbull, but it is not clear that these data represent the maximum that can be achieved. Doing such experiments in space has several advantages over the droptube: the available time is much longer, the sample can be observed and measured directly, and the experiment may be repeated by remelting the same sample.

An attempt to determine the maximum undercooling in iron and nickle-based alloys was made by Flemings and Shiohara of the Massachusetts Institute of Technology (MIT) on STS-61C using the modified SPAR electromagnetic levitator mounted on the MSL. Szekely and Kang (MIT) have completed a computer analysis of the stirring in such melts resulting from the levitation forces and will attempt to observe these flows in levitated melts. Due to a failure in the cooling loop, the apparatus overheated and shut down prematurely. One sample was partially processed and little information could be recovered. Apparently little undercooling was achieved and nucleation appeared to have originated at a site on the surface. The resulting dendrites were curved with non-orthogonal secondary arms. A molten glass coating, intended to serve as a getter for any impurities in the sample, was discolored and covered only a portion of the sample.

Subsequent ground-based work has succeeded in developing cinematographic techniques for observing and measuring solidification velocities and for obtaining time-resolved details of the recalescence. These techniques will be incorporated into the next generation of flight experiments for this type of study.

In attempting to plan and model microgravity experiments, it has become apparent that there is a paucity of thermophysical data for materials in their molten state. Now that many industrial scientists are beginning to use the new supercomputers to model solidification of complex castings in order to predict microstructure and unrelieved stress, this lack of reliable thermophysical properties data is a serious impediment to progress in this field. Aside from their practical importance, careful measurements of physical properties can give insight into the fundamental behavior of matter. Recall that measurement of heat capacity of solids as a function of temperature led to the development of the quantum theory for solids. Precise diffusion measurements made by the Germans on SL-D1 established the correct physical theory for diffusion in liquids and gives new insight into the structure of liquids. Containerless processing offers several novel techniques for obtaining such data.

For example, at Rice University, Margrave has developed techniques for obtaining heat capacity and total enthalpy of levitated melts by observing their cooling curves. Cezairliyan and Miller of NBS have developed a millisecond pulse technique for measuring heat capacity, electrical resistivity, thermal expansion, and spectral emissivity as a function of temperature. Also, the temperature and energies involved in various phase transitions can also be obtained. The sample in the form of a short wire is rapidly heated by the passage of a current. The pertinent properties are measured with high-speed multispectral photometers.

The technique has been very successful on Earth for temperatures up to and slightly above the melting point. As the sample melts, however, it sags before measurements are possible. Several flights on the KC-135 have extended the measurement only slightly higher into the liquid range before the molten bridge was lost. The reason for this loss is still not clear. The design of the system may be such that the molten sample is inherently unstable. On the other hand a simple g-spike could have caused the loss of the liquid zone. A new design with better stability properties is being developed.

Glasses and Ceramics

Most solids prefer to have their atoms arranged in some regular or periodic structure, which is a state of lowest energy. This order exists on a macroscopic scale for most practical semiconductors which require single crystalline material. In metals and alloys, this order usually exists only on a microscopic scale over individual, randomly-oriented, single-crystalline grains which form the microstructure. Glasses, on the other hand, are characterized by a lack of order in their atomic structure. This allows the formation of bulk amorphous materials without grain boundaries that would scatter light, trap electrons and holes, and be subject to chemical attack. People generally tend to think of glasses as transparent, non-conductive materials, but this is because materials with these properties form glasses much more readily than metallic systems. However, certain metallic systems, if quenched rapidly enough, will also form amorphous or glassy solids. It should be noted that these metallic glasses look and behave like metal, i.e., they are not transparent, but also do not have individual grains or grain boundaries. This gives them unique chemical, mechanical, and magnetic properties.

Ceramics are generally thought of as insulating, refractory materials which have compositions similar to glasses, i.e., they consist primarily of oxides, silicates, borates, etc., and are generally good glass formers. Because of their high-melting temperatures, it is generally more efficient to bind together small crystallites in a glassy matrix to form a useful material rather than form an amorphous material from the melt. Modern advances in material science has made it difficult to classify materials unambiguously. Not only do metal glasses exist, but the recently discovered high temperature superconductors based on the yttrium-barium-copper-oxide system are technically ceramics, yet they offer no resistance to electral current at temperatures below 90-95 Kelvin.

In order to form a glass, it is necessary to bypass the equilibrium, or ordered phase when cooling from the melt and freeze the atoms in their disordered liquid configuration. Since there is an energy barrier that must be overcome to form a solid nucleus of critical size, it is possible to undercool a melt below its equilibrium freezing point by eliminating all low-energy nucleation sites such as impurity solids or crucible walls. Since viscosity increases rapidly as the temperature is lowered, the atoms eventually get too sluggish to rearrange themselves in an ordered crystalline lattice and a glass results.

Good glass formers are characterized by having only a small energy difference between the ordered and disordered configuration and having a high viscosity to inhibit crystalline growth. Reluctant glass formers do not have these properties, but can be "tricked" into forming a glass if they are cooled rapidly enough so the atoms simply do not have time to arrange themselves in an ordered structure while they still have sufficient thermal energy to move around.

Microgravity offers several advantages for the study of glasses and ceramics. Many glass-forming systems have immiscible liquid phases which tend to separate in gravity. Containerless processing can be used to eliminate wall-induced nucleation sites, and thus increase the amount of undercooling in reluctant glass-forming systems. Many high-temperature glass and ceramic systems are virtually universal solvents in their molten state, hence containerless or quasicontainerless (floating zone) processing can be used to eliminate container-induced contaminants in order to produce ultrapure glasses. Finally, physical properties such as diffusion coefficients can be measured accurately without convective contributions. Viscosity and surface tension can be measured in the undercooled state using containerless methods.

The development of containerless processing techniques that can operate over large temperature ranges has proven to be a formidable task. Since most of the materials of interest are not good conductors, electromagnetic levitation is not practical. Acoustic levitation has been the method of choice since most glass-forming systems require an oxidizing atmosphere such as air. The difficulty lies in the fact that the speed of sound in the gas varies with temperature, hence it is difficult to maintain the resonance conditions required to form the "energy well" that contains the sample over wide temperature excursions (up to 1600C).

Considerable research into this problem is being done at JPL. Hybrid acoustic and electrostatic levitation schemes are being explored. Intersonics developed a single axis acoustic levitator (SAAL) furnace that forms an energy well by using a reflector to form an interference pattern between the incoming acoustic wave and the reflected wave. This technique has the advantage on always being "in-tune" and is not affected by changing resonance conditions. The SAAL has been tested several times on SPAR flights and on STS-7 and STS-61A using the MSL. A number of unforeseen problems were identified and corrected on these flights and samples were finally successfully levitated and melted near 1600C.

The single axis technique provides excellent stability along the sound axis, but the radial restoring forces (principally the Bernoulli effect) are weak and the samples are frequently lost during heating or cooling. A new concept is being developed by Intersonics that uses opposed acoustic drivers along 3 orthogonal axes to create a three-dimensional energy well. By varying the phase of the driver, the sample may be manipulated and rotated. This concept will be tested on USML-1.

The most interesting scientific result obtained with this device on STS-61A was an attempt by Gac (LASL) to spheroidize a glass shell that had a dimple purposely placed at one point. The shell appeared to become spherical when it melted, but then the internal bubble moved to one side and disappeared. The recovered sample had a beautiful fire-polished surface but showed no trace of the bubble. Post flight analysis revealed that one of the silicon carbide glow-bar heaters in the furnace had developed a higher resistance and apparently was not putting out as much heat as it should. The resulting thermal gradient apparently caused the bubble to migrate by thermocapillary effects toward the hotter side and through the wall. Although this was not the expected result, it did demonstrate that it is possible to remove bubbles that may form in glass melts in microgravity by thermocapillary effects.

BIOTECHNOLOGY

There are several facets of biotechnology that are being impacted by microgravity research. First, it is known that significant effects in living organisms occur in the virtual absence of gravity. The study of such effects, particularly as they pertain to the health and well-being of crew on extended missions, is primarily the responsibility of the NASA's Life Sciences Division. There is, however, an overlap with Microgravity Science and Applications Division as such studies approach the microscopic behavior of living systems at the cellular level. There is also the possibility for developing enhanced capability for fusing as well as separating cells in microgravity.

The primary focus of the microgravity program in biotechnology, however, is the growth of protein and other macromolecular crystals . In some very simple experiments, evidence of superior ordering of the crystalline lattice that could be achieved in microgravity was obtained. Since the only direct source of knowledge of the molecular structure of complex proteins is derived from x-ray diffraction data obtained from crystallized proteins, this could have enormous implications for understanding the biological function of important proteins at the molecular level. In addition to fundamental knowledge, such information provides the basis for rational drug design, the development of new vaccines, and protein engineering.

Cell Science

There are several reasons for developing a facility for culturing cells in a microgravity environment. The first and most fundamental is to study the response of the cell itself to the absence gravity and to clarify some of the earlier findings of the Soviets and the Germans that indicate significant changes in cell function in microgravity. What is not clear from these early experiments is whether the cell itself responds to the absence of gravity, or whether the changes are in response to the altered transport conditions as buoyancy effects are suppressed. The flows in the bioreactor being developed at the Johnson Space Center (JSC) are minimal and well-characterized; thus, the system should provide the control necessary to sort out the various effects in such experiments. Also, the bioreactor can serve to maintain viable cell cultures for cell fusion experiments as well as for various low-gravity separation experiments.

In their development of the bioreactor, JSC scientists have introduced a new concept for maintaining suspension cultures with a minimum of shear flows which are damaging to cells. Instead of stirring the mixture with impeller blades, as is conventional practice, they slowly rotate the vessel about a horizontal axis so that the suspended cells are continually being gently swept back up as they fall by the rotating fluid. A similar concept was originated by Lacy (MSFC) and Otto (UAH) to simulate microgravity in their work on immiscible metals. It has subsequently been used by Vanderhoff to produce large monodispersed latex spheres on Earth and by Bier to stabilize flows in his commercial isoelectric separator. Using microcarrier beads for cells that can only grow when attached to a surface, scientists of JSC and the University of Texas Health Science Center have been able to culture cells in three dimensional, tissue-like arrays not possible in conventional culture systems. Additional instruments are being built to be made available to other interested users.

Separation of Biomaterials

The ability to separate and purify various macromolecules, cells, and cell components is key to many fundamental studies in the biological sciences as well as to the production of pharmaceutical products. Of course, modern technology has developed many ways to accomplish such separations on Earth, some of which were spawned by the space program.

For example, Professor Milan Bier, Director of the NASA-sponsored Center of Excellence for Separation Science at the University of Arizona, originally proposed his recirculating isoelectric facility (RIEF) as a concept for a space-based separation facility because he did not think it would be possible to control the convective flows in the separation chamber. In developing this concept in preparation for a flight experiment, he found that such flows could in fact be controlled by placing membranes in the chamber. A simplified version of this concept, which also rotates the chamber to simulate microgravity by confusing the gravity-driven flows, is now being marketed by Bio Rad. So far, more than 250 such units have been sold all over the world and are setting standards for protein purification.

The McDonnell-Douglas continuous flow electrophoresis system (CFES), that flew a number of times on the Shuttle, has been overtaken by alternative technology. This is bound to happen to many concepts in a fast-paced field such as biotechnology. While offering a significant improvement in throughput over convectional ground-based electrophoresis machines, CFES could not compete with some of the newer chromatographic techniques that do not require waiting for a flight opportunity.

A great deal was learned about electrophoresis technology from the CFES flights, however. For example, researchers found significant spreading of the sample stream at high concentrations that they now understand as an electrohydrodynamic effect brought about by the mismatch of electrical properties between the sample and buffer stream. These effects had not been apparent before since on Earth we could not operate with the higher concentration samples because of density mismatch. However, this effect has profound importance in the electrophoretic separation of cells.

Continuous flow electrophoresis is one of the few techniques for the separation of cells that does not in some way damage the cells. To maintain viability, cells must be kept in a near-isotonic solution (salt concentrations comparable to that found in living organisms). Such concentrations of salt can generally not be tolerated in electrophoresis buffer solutions because of the heating brought about by the higher current flows that would result from using a more conductive buffer. Therefore, cell electrophoresis will always be subject to these electrohydrodynamic effects that spread the sample stream and degrade resolution. This effect could well be a limiting factor in Earth-based electrophoretic separation of cells.

This electrohydrodynamic effect can be used to advantage in a recently patented, moving-wall electrophoresis chamber developed by Rhodes (MSFC). In conventional electrophoretic chambers, wall effects spread the sample and degrade the resolution of the machine; therefore, it is necessary to restrict the sample to the center of the separation chamber. The conductive mismatch causes the sample to migrate toward the walls where unwanted spreading occurs. In Rhodes' concept, the wall effects are eliminated by moving the walls along with the flow, hence resolution is not degraded by this migration. Unfortunately, since there is no effective flow to stabilize the system against buoyancy-driven convection, the system will have to be operated in microgravity. This concept will be tested in the USML series.

Cell Fusion

A collaborative effort is being developed with the Germans to explore electrofusion in microgravity. Electrofusion is one of the techniques used for producing hybridomas which are the union of a lymphocyte activated to produce a particular antibody with a myeloma or tumor cell. This union produces an immortal cell line for the production of monoclonal antibodies (MCAs).

Although the production of MCAs is now a fairly mature technology, it is not always easy to obtain viable fused cells. In electrofusion, cells are first subjected to a high frequency alternating current to bring them together and align them. Then they are subjected to one or more high voltage pulses that punch through the cell membrane. Following this, the high-frequency current is again applied for a minute or so to hold the cells together while their punctured membranes heal, hopefully with two of the desired cells fused together.

This approach is rather harsh treatment for the cells and the yield of viable cells with the proper characteristics is small. A more efficient method would be highly desirable.

It is speculated that there would be less tendency for the cells to separate due to their density differences in microgravity. Therefore, the time and intensity of the high frequency aligning field could be reduced and it may only be necessary to apply a single Direct Charge pulse to cause fusion. All of this should increase the viability of the fused hybridomas and yield a more efficient process.

Zimmermann of the University of Wurzburg has obtained some preliminary but encouraging results on the German SL-D1 mission and on a TEXUS rocket flight. A more elaborate experiment is being planned for the German SL-D2 mission in which Sammons of the University of Arizona will be a co-investigator. Additional studies on electrofusion will be carried out by Sammons on the KC-135 in which the cell fusion process will be observed with a special microscope stage during the low-gravity parabolas.

If these experiments indicate that cell fusion is a viable candidate for additional microgravity experimentation or possible application, an electrofusion device will be included in the Biotechnology Facility to be supported by the bioreactor.

Macromolecular Crystal Growth

The biological function of macromolecules, including deoxyribonucleic acids (DNA), polypeptides, enzymes, hormones, and other complex molecules, is determined by their three-dimensional conformation or structure. In order to understand how living organisms function at the molecular level, it is necessary to determine this structure.

By understanding how the molecules function, it is possible to find methods for altering or controlling this function. Many pharmaceuticals and agrichemicals operate by blocking active sites on a specific target molecule. The ability to interact with and block active sites depends on the fit between the agent and the target molecule. The search for effective control agents or new drugs has historically been a trial-and-error procedure based on insight gained from previous successes. However, if detailed knowledge of the target molecule can be obtained, it should be possible to design a molecule to fit the active site, just as it is easier to make a key if you understand the lock. The technology of rational drug design is still in its infancy, but is attracting intense interest from the major pharmaceutical houses, the biotech industry, and the agrichemical companies.

The ability to modify or design new molecules to obtain enhanced enzymatic or other biological activity also depends on structural information. For example, by selectively adding disulphide bridges to strengthen a macromolecule, it may be possible to develop enzymes that remain active at higher temperatures or that are more resistant to a harsher chemical environment. Molecules may be designed for specific purposes, for example to bind to or break up unwanted chemicals. This promising but immature field of protein engineering also depends on being able to determine the 3-dimensional structure of macromolecules.

At the present, the only method available to researchers for determining this structure is x-ray diffraction data obtained from small crystals of the material in question. The periodic array of molecules in the crystalline lattice diffracts x-rays, forming a distinctive pattern that can be recorded on film or on electronic area detectors. Computers can convert these patterns into electron density maps from which the structure can be deduced.

Max Perutz spent much of his professional life taking diffraction data manually and unraveling the structure of hemoglobin, for which he won the Nobel Prize. Now, with today's sophisticated x-ray detectors and powerful computers, structures can be determined in a few months provided good crystals of the protein in question are available. This has remained the rate limiting step in determining protein structure. To date, structures of only a few hundred unique proteins have been determined and these represent proteins that are easy to crystallize. There are literally thousands of important proteins that have not yielded to this process, primarily because of the inability to grow crystals of sufficient size and quality.

Proteins in general are difficult to crystallize. There are a number of methods for forcing them out of solution. However, they have small ordering energies, hence there is a tendency for proteins to precipitate in an amorphous state rather than form crystals. Crystals, when they do form, tend to be very fragile because of the weak attraction between their molecules and because many protein crystals contain up to 50-60% water. For this reason, they must remain in their mother liquor or saturated growth medium in which they are in equilibrium.

Highly purified proteins of interest are generally very difficult to prepare, extremely expensive, and are often available only in milligram quantities. The purified protein solution is mixed with a precipitating agent and deployed as pendant drops or placed in a dialysis membrane. Protein is forced out of solution by addition of a precipitation agent or by removal of water. Ideally, one would like to grow a crystal with good long range order (high degree of perfection) with dimensions of a few millimeter on each side. In practice, many proteins that do crystallize, for reasons that are not yet understood, tend to stop growing after they reach a few hundred microns in size. Other proteins will grow into larger crystals, but have poor x-ray diffraction resolution which is caused by internal disorder. This prevents an accurate structure determination.

There are a number of reasons to believe that microgravity may benefit macromolecular crystal growth. Since proteins are slightly more dense than water, the crystals will generally settle to the bottom of the growth system unless the system is stirred. This will introduce non-uniform growth conditions, which as shown in past experiments with small molecular crystallization, can cause growth defects. Often two or more crystals settling to the bottom will merge into a multigrain mass which is useless for x-ray work.

Significant convective flows are driven by the solutal gradient as the crystal takes up protein from the growth solution, leaving a less dense depletion layer at the growth interface which will rise because of gravity. The role of these convective flows in the growth process, particularly with regard to defect formation, is not understood. Agitation, or possibly even the natural convective flows, appears to increase the number of new crystallites that form and compete for the available protein. Since smaller particles grow faster than larger particles in a supersaturated solution, the presence of secondary crystals will inhibit the growth of the primary crystal.

Interest in microgravity for the growth of protein crystals was sparked by Littke of the University of Freiburg, who grew significantly larger protein crystals on Spacelab-1 than could be grown on Earth using the same liquid diffusion process. The space-grown crystals were also fewer in number and the crystals that grew freely seemed to be of higher quality than those that grew attached to the container wall.

Several protein crystal growth experiments were conducted on early Shuttle flight by Bugg (UAB) and his collaborators. More than forty investigators have volunteered to join Dr. Bugg's investigation in order to see if they can get improved crystals of their protein of interest. This is indicative of the intense interest in protein crystallization. These early experiments were conducted in a simple hand-held device and were primarily intended to explore various concepts for growing crystals from a fraction of a milliliter of growth solution. No attempt was made to control the temperature during the process. In spite of this lack of control, some very excellent crystals were obtained from human serum albumin, human C-reactive protein, canavalin, and concanavalin B, which appeared to diffract to higher resolution than those grown on Earth.

A new protein growth apparatus has been developed and will be flown on STS-26 and subsequent flights whenever possible. To provide temperature control, the growth apparatus has been designed to fit inside the refrigerator module originally designed by McDonnell-Douglas to store proteins to be separated by CFES. The protein solution and the precipitating agent are stored separately and mixed on orbit. This prevents growth from starting during the storage in unit gravity prior to launch or during the ascent phase.

Perhaps the most significant contribution NASA can make to the science of protein crystal growth is the multidisciplinary approach that is being brought to bear on the problem. For the first time, small molecule crystal growers, fluid dynamicists, physical chemists, and optical physicists are collaborating with the protein chemists and protein crystallographers to attack this important problem. Some of the discipline developed by the crystal growers from the semiconductor industry, such as the determination of phase diagrams or solubility curves to guide the growth process, is being introduced.

Meehan (UAH) has developed solubility curves for lysozyme (a model system) as a function of temperature, pH, and concentration of precipitating agent. From such curves, optimum growth conditions can be determined. Pusey (MSFC) has developed an efficient system for determining solubility curves for proteins of practical interest, which are available only in limited quantities.

Carter (MSFC) has found a technique for controlling the nucleation rate, hence the number of crystals that will form, by controlling the rate at which supersaturation of the growth solution is approached. Witherow (MSFC) has developed optical methods for determining protein concentration, for detecting nucleation, and for measuring the convective flows in small droplets. Rhim (JPL) has grown protein crystals in small droplets that are suspended electrostatically. Rosenberger (UAH) is exploring the use of temperature control to intervene after the first nucleation event in order to prevent additional nucleation events. Suddeth of the Georgia Institute of Technology is developing methods for actively controlling the growth conditions.

The results of this technology will be combined into the development of an Advanced Protein Crystal Growth Facility that will be tested in the USML series and eventually flown on the Space Station. Since some of the proteins that are eventually grown in space may be too fragile to be returned, consideration should be given to analyzing them in orbit and sending the x-ray diffraction data back to Earth. The use of robotics and telescience to assist in this laborious task is being explored.

VI.

FLIGHT FACILITIES DEVELOPMENT

As discussed in Chapter III of this report, the NASA Microgravity Materials Science Assessment Task Force (NMMSA) made several significant recommendations regarding the MSAD Program. This chapter discusses the Task Force's recommendation to develop facility-class hardware that could be used during the USML flight series and ultimately on the Space Station or a CDSF.

The Space Shuttle, the Spacelab, the manned-Space Station, and a CDSF will constitute an integrated system that permits an evolutionary approach to microgravity research in low-Earth orbit. Experiments can be developed on the ground, tested and refined aboard short-duration Spacelab flights, and then deployed on the Space Station for long-duration operation. The sequence ensures that maximum scientific return from planned investigations, encourages the growth of a vigorous microgravity research community, and increases the chances for identifying new techniques and processes of commercial value to ground-based U.S. industry.

A flight facility is defined as an assembly of subsystems that can support various experiment modules that have common requirements. An experiment module is designed to conduct a series of experiments to specifications provided by the various Principal Investigators. Using this modular approach we can retain the flexibility required to accommodate new scientific requirements as they evolve during the lifetime of the facility.

Six facilities, which were initiated in FY 1988 and included in the funding request for the program for FY 1989, are the Modular Multizone Furnace Facility, the Modular Containerless Processing Facility, the Advanced Protein Crystal Growth Facility, the Biotechnology Facility, the Fluid Physics/Dynamics Facility, and the Modular Combustion Facility.

Facilities are also being considered for polymer science and fundamental physics and chemistry research. However, it has not yet been determined whether such experiments could be accommodated on the planned facilities or if conceptually unique facilities are required.

The program's highest priority is the Modular Multizone Furnace Facility. This will consist of a collection of furnaces for growing high-quality semiconductor crystals for solidifying various alloys and composites, and for measuring thermophysical properties of metals and alloys. A small diameter (2 cm) version of the crystal growth furnace and the alloy solidification furnace are being developed for utilization on the USML series of flights. These furnaces are modular in nature and some may be reconfigured on orbit to accommodate different experiment requirements. In addition to providing an early scientific return, these flights will be used to evaluate the modular design concepts that will be needed when the furnace facility will remain in orbit.

The Modular Containerless Processing Facility will accommodate a variety of experiments that require the positioning and manipulation of samples without physical contact. Acoustic, electromagnetic, and electrostatic fields will provide the forces required to manipulate the sample and to overcome the residual spacecraft accelerations in order to maintain the samples' position during the process. Experiments to be conducted in the Modular Containerless Processing Facility range from tests of theories that describe the behavior of liquid drops to the processing of molten materials at high temperatures.

Two experiment modules that will eventually go into this facility, the Drop Physics Module and the Acoustic Levitation Furnace, are being developed for the USML series of flights. In addition to an early science return, this series of flights will allow us to develop levitation and heating techniques for very high temperatures and the measurement technology needed for the more ambitious experiments planned for Space Station.

The Advanced Protein Crystal Growth Facility will incorporate the new technology being developed in our ground research programs in order to sense and control nucleation and growth of protein crystals. Electrostatic suspension techniques are being explored to deploy the droplets of growth medium without physical contact to eliminate spurious nucleation sites. The objective is to limit nucleation in the protein droplet so that a single crystal develops, and then grow that single crystal under carefully controlled conditions to obtain the highest degree of long range order in the crystalline lattice. This order determines the precision with which x-ray crystallographers can determine the structures of these complex biologically active molecules which is needed in order to design new drugs for controlling this activity.

The Biotechnology Facility will consist of one or more bioreactors and associated equipment for supporting cell science investigations in microgravity. This will allow a detailed study of the response of various cells to microgravity under carefully controlled conditions which can resolve some of the provocative results obtained by the Soviets on Salyut and the Germans on D-1 which indicated dramatic changes in cell function in microgravity. Also the bioreactors will serve as cell maintenance systems to support advanced cell separation and cell fusion processes that can take advantage of microgravity.

The Fluid Physics/Dynamics Facility will accommodate a variety of experiments in fluid flow and transport phenomena. An experiment module to study surface tension driven convection without the complicating effects of buoyancy driven convection is being developed for a series of experiments to be started on the USML flights. Other experiments being considered for such a facility include flow and property measurements of multi-phase fluids, electro-hydrodynamics, behavior of fluids near critical phase transitions, and tests of various stability criteria. Such experiments will enhance our understanding of the behavior of fluids in microgravity which is essential to developing processes that take full advantage of the microgravity environment.

The Modular Combustion Facility will provide suitable containment and diagnostics to study combustion phenomena in microgravity. Such knowledge is essential for developing appropriate fire safety criteria for manned laboratory operation and to determine the best methods for dealing with a fire should one develop. Also, such experiments allow the study of fundamental phenomena involved in combustion under diffusion controlled transport which vastly simplifies the measurement and analysis. Experiments will include solid surface combustion, smoldering combustion, pool burning, droplet combustion, and particle cloud combustion. Preliminary combustion experiments are being developed for Shuttle Middeck and Spacelab. In addition to providing early data, these experiments will be used to develop concepts for the Space Station facility that will permit interactive experimentation.

Recently, polymer scientists have begun to take an interest in microgravity research in order to develop an increased understanding in the processes carried out on Earth. For example, they would like to be able to measure directly the extensional viscosity of a variety of polymers which behave as non-Newtonian fluids. This quantity is important in many processes ranging from the pulling of fibers to ink-jet printing and paint spraying. Most of these processes evolved from years of empirical cut-and-try methods. Knowing the extensional viscosity and how to control it would enable plant engineers to design more efficient processes. The crystallization of certain polymers also shows promise in the search for non-linear optical material for optical logic devices and other advanced applications. It is thought that the microgravity environment might provide better control in the crystallization of polymers which would result in more homogeneous crystals with fewer defects. Experiments planned for the USML series will evaluate some of these concepts and will determine whether future experiments can be carried out in presently identified facilities, or if a new facility will be required for polymer science.

Several individual microgravity experiments are currently being developed to provide critical tests of the equivalence principle, which is the fundamental assumption in Einstein's theory of relativity, and Wilson's recent Nobel Prize theory of the universality of condensed matter behavior near a second order phase transition. These experiments, and others designed to challenge contemporary laws of physics and chemistry, may eventually require a drag-free, free-flying satellite to realize their ultimate accuracy. However, short-duration tests on the USML series and longer- duration tests on the Space Station are important steps toward evolutionary development.

All of the facilities that accommodate experiments requiring more that a few days of microgravity will be designed to operate in a man-tended mode so that they could be flown during the build-up phase of Space Station or on a CDSF.

A Flight Project Management Plan is being implemented to guide the microgravity hardware for flight experiments. The document, entitled *Flight Project Management Plan,* is used to define the activities and procedures required for MSAD-developed experimental hardware facilities and science experiment modules.

VII.

ADVANCED TECHNOLOGY DEVELOPMENT

Flight experience with the current hardware inventory has shown that a front-end investment in technology specific to the microgravity program is essential. To that end NASA is working on Advanced Technology Development (ATD) tasks to create or refine equipment that will enhance the scientific fidelity and quality of future flight experiments. This includes applying existing and new diagnostic techniques/technologies to develop species concentration, temperature and flow velocity measurement systems for fluids and combustion experiments; high-temperature materials; vibration isolation; non-contact temperature measurement; high-resolution, high-frame rate video system; and interface measurements.

A two-day Non-contact Temperature Measurement Workshop was held in late April of 1987. Each of six science disciplines was surveyed for their unique temperature measurement requirements. Three categories of experiments demanding a non-contact temperature measurement technique include levitated samples, crystal growth, and gaseous or fluid flows.

A combustion diagnostics workshop was held at LeRC in July of 1987, and was attended by invited members of the diagnostics and microgravity combustion science communities. As a result of this activity, the baseline science requirements and initial areas of technical development have been defined.

One of the requirements of space processing is the investigation of materials that are formed at very high temperatures (greater than 2000 degrees C). It is imperative that materials and fabrication technology be explored that will allow the development of furnaces with capabilities to provide these temperatures in a reliable, well-controlled way. Studies will be initiated to determine the properties of high-temperature materials that can be used in furnace construction.

Furnace technology research also has been initiated. Plans have been developed to start the evaluation of new heater concepts for the 1600 to 3000 degrees C range, evaluate new temperature sensing and control concepts, and develop thermal models that can be used to evaluate furnace concepts. The next step will be to develop a test bed where various concepts and materials can be studied.

The objective of the Vibration Isolation Technology ATD activity is to develop technology which will provide controlled, well-characterized, low-gravity environments for microgravity science experiments. It appears that the dynamic background of vibrations and other residual accelerations that have been observed on manned carriers in low-Earth orbit will be significant impediments to many experiments requiring extended periods of low-gravity environment. The three principal thrusts of the program which address selected aspects of the problem are the development of vibration isolation and damping technology, the development of reactionless mechanisms and robotics, and the analysis of selected experiments to define sensitivity to residual acceleration.

During 1987, the primary activities addressed the definition of requirements and initiation of selected preliminary studies. In 1986, the need for the development of high-resolution, high-frame rate video technology (HHVT) was recognized. The HHVT would be used by microgravity science and applications investigators on future Space Shuttle experiments and for ultimate use in Space Station laboratory.

The objective of the HHVT ATD project is to provide advancements in technology to remove some of the constraints on the amount of high-speed, detailed optical data recorded and transmitted from microgravity science experiments. The HHVT ATD project began in mid-1987 with LeRC as the lead center, MSFC and LaRC as performing support centers, and the JPL as a consulting support center.

The user requirements survey is near completion. The assessment of existing video technology has been completed and is being kept up-to-date. A conceptual design for the near-term HHVT system is close to completion.

Various electrostatic sample positioning technologies which will be used for material processing experiments in space are also being developed. The microgravity environment attainable in space can be used for various materials science experiments if these materials, especially those highly reactive materials, can be positioned and controlled free from contact with container walls. Such contactless methods will protect the sample from undesirable contamination and reduce heterogeneous nucleation and deformation caused by physical contact with the container. Since electrostatic force is used as the main control force, the electrostatic positioning technique can operate in vacuum as well as the gaseous medium in essential.

In contrast to the electromagnetic levitation which requires samples to have relatively good conductivity, both conducting and nonconducting samples can be positioned in the electrostatic positioning technique as long as samples carry sufficient electric charges. Further advantage of electrostatic levitation is the absence of streaming or mixing within or around the sample with is normally encountered in the acoustic and electromagnetic levitation systems. The major accomplishment during 1987 was the construction of an electrostatic-acoustic hybrid system and its application to the charged drop dynamics and the protein crystal growth from the levitated solution.

The objective of the Interface Measurements ATD is to develop techniques to measure the shape and position of the liquid-solid interface in crystal growth. The interface position is determined by furnace conditions and the sample thermophysical properties. The interface shape is interactive with its position in the furnace and the mass transport in the liquid.

The present effort is in two parts. One effort is looking at measurement of the interface shape and position by rapid solidification after a period of normal growth. This presents a definitive measurement but it is destructive to the crystal. The other technique is non-destructive to the crystal and uses radiography to examine the interface. This technique is not as definitive but computer enhancement techniques and calibration samples are being used to improve the measurements.

VIII.

COMMERCIAL AND INTERNATIONAL ACTIVITIES

Two key aspects of the future Microgravity and Science and Applications Program will be the enhancement of commercial and international programs. Both aspects of the current program have been studied and will continued to be emphasized as MSAD program planning evolves. This chapter discusses MSAD's program approaches for commercial and international efforts.

COMMERCIAL ACTIVITIES

Space research has great potential importance to future U.S. competitiveness in the international market. Material Science is an area of particular commercial interest. There is widespread agreement that the U.S. must pursue a vigorous microgravity research program and thus be positioned to exploit new materials, techniques, and process technologies revealed by space experiments. Joint government and industry programs at least as ambitious as those of the U.S. are already underway in Europe, Japan, and the Soviet Union. These programs are well-planned, well-funded and enjoy substantial political support from their respective governments.

The research capabilities embodied in the Space Transportation System (STS) and Spacelab, and now emerging in Space Station and CDSF coupled with an aggressive U.S. program in technology advancement will allow U.S. researchers to compete effectively with international groups.

NASA has long encouraged university and industry participation in space research through Announcements of Opportunities, Dear Colleague Letters, Joint Endeavor Agreements, Technical Exchange Agreements, and Industrial Guest Investigator Programs. An even greater degree of private sector participation in space research and involvement with Space Station planning is being pursued.

The NASA Advisory Council's Task Force for the Commercial Use of Space (Vanderslice report) stressed the linkage between building a sound research base and the participation of industry in developing the space resource. The MSA program has increased cooperation with the OCP in four main areas in support of the commercial use of space. These areas include the coordination of outreach activities, joint hardware development, joint research funding, and improving NASA utilization of the JEA quid pro quo opportunity.

The development of commercial uses of space will depend primarily on two factors: 1) a thorough understanding of the effects of microgravity on processes and materials and, 2) the availability of well-characterized and versatile equipment that can exploit microgravity effects. The relationship between the science program and the commercial program is an interactive one. The commercial community requires timely research results and information on the benefits and limitations of the microgravity environment. Similarly the research community needs industry guidance concerning the materials and processes of interest.

Efforts are underway to coordinate outreach activities and improve communications between the respective science and commercial communities. The development of multiuser (facility-class) hardware for the Space Station or a CDSF will also benefit from the early coordination of user requirements. The OCP Commercial R&D Enhancement Activity is being closely coordinated with related MSAD programs at the various NASA Field Centers.

NASA is currently examing a variety of ways to speed progress toward Space Station scientific goals. One possibility is the extension of Shuttle flight duration. Another approach is the use of complementary space facilities developed by the private sector to augment existing Spacelab capabilities. While these alternatives provide a range of new options as well as new requirements, only the resumption of Shuttle flights will reduce the current backlog. MSAD is cooperating with other NASA groups to ensure that the most productive mix of experiments with the greatest scientific and commercial return are flown.

INTERNATIONAL ACTIVITIES

The Soviet Union has enjoyed an almost continuous presence in space since 1976, and it has been intensively developing microgravity processing techniques. Much of its hardware is now in the third generation and many processes have had the advantage of repetitive experiments and are undergoing continuing refinement. The Soviets have also increased their overtures to the Japanese, the Europeans, as well as U.S. researchers and commercial groups to fly experiments on board Soviet craft.

International cooperation provides one, if not the best, mechanism to defray the significant costs of hardware development while allowing U.S. co-participation and access to the science data. In addition, some of our foreign partners are very capable of contributing valuable technology and expertise. Both of these considerations are vital to maintaining U.S. leadership in space. However, caution must be exercised to avoid transferring technologies that are critical to national defense or could potentially damage the competitive posture of the U.S.

The SL-D2 (2nd German Spacelab) flight is scheduled to fly in December 1991. Much of the hardware is retained from the SL-D1 mission. However, the BIOTEX facility will be added to study electrophoresis, cell culturing, and electrofusion. A working group has been officially established between NASA and the German Federal Ministry for Research and Technology (BMFT) to explore areas of cooperation in this and future missions.

The Japanese Spacelab (SL-J) flight is scheduled to fly May 1991. The materials processing hardware was adapted from European hardware and is largely generic. The Japanese have initiated a new international cooperative program to coordinate Japanese ground-based research and hardware development with other countries. A science working group between NASA and the Japanese Space Agency (NASDA) has been established to explore possible U.S.-Japanese interactions.

There are cooperative agreements in place with the German BMFT, the Japanese NASDA, the European Space Agency (ESA), and the French National Center for Space Studies (CNES) to fly various pieces of foreign hardware on the IML flights beginning in February 1991. The hardware will be flown without cost to the foreign agencies and will be available to U.S. as well as to international principal investigators.

Finally, through an agreement with the CNES, the MEPHISTO experiment will be flown 6 times with a joint U.S. and French investigative team. This highly sophisticated solidification experiment makes use of the nanovolt Seebeck Effect signal generated at the liquid-solid interface to measure undercooling at the growth front from which information pertaining to growth kinetics, interfacial stability and defect formation can be obtained.

For the future, the Phase I manned Space Station will constitute an international scientific laboratory in space. Circling the globe at an altitude of 220 miles, the Station will incorporate four pressurized modules--two provided by the United States, and one each provided by ESA and Japan. One of the U.S. modules will be devoted to habitation. The other three modules will contain extensive laboratory facilities for experiments in materials science and life sciences; research areas that exploit the microgravity environment of the Station and benefit from human interaction and operation.

As NASA prepares for the 21st century, the Space Station offers a unique opportunity for scientific research in an extended duration microgravity environment. This will enable researchers to initiate comprehensive studies on a wide range of materials and processes. For the first time, we will be able to conduct experiments in an interactive mode, allowing results from one set of experiments to guide the subsequent experiments. The Space Station is truly the centerpiece of our activities in space.

The integrated system comprised of the Space Shuttle, Spacelab, CDSF, and the Space Station will permit an evolutionary approach to microgravity research in space. Experiments can be developed on the ground, tested and refined aboard short-duration Spacelab flights, and then deployed on the Space Station for long-duration operation. This sequence ensures the maximum scientific return from planned investigations, encourages the growth of a vigorous microgravity research community, and increases the chances for identifying new materials and processes of scientific or commercial value.

APPENDIX

ACRONYMS AND ABBREVIATIONS

AADSF	Advanced Automated Directional Solidification Furnace
ATD	Advanced Technology Development
CCDS	Centers for the Commercial Development of Space
CDSF	Commercially Developed Space Facility
CNES	Centre National d-Etudes Spatiales (French National Center for Space Studies)
DWG	Discipline Working Group
ELV	Expendable Launch Vehicle
GAS	Get Away Special
HHVT	High-Resolution High-Frame Rate Video Technology
IML	International Microgravity Laboratory
JEA	Joint Endeavor Agreement
JPL	Jet Propulsion Laboratory
LaRC	Langley Research Center
LeRC	Lewis Research Center
MICOM	Missle Command
MMPF	Microgravity Materials Processing Facility
MSL	Microgravity Science Laboratory or Materials Science Laboratory
MSA	Microgravity Science and Applications
MSAD	Microgravity Science and Applications Division
NASA	National Aeronautics and Space Administration
NASDA	Japan Space Agency
NIH	National Institutes of Health
NMMSA	NASA Microgravity Materials Science Assessment Task Force
NRA	NASA Research Announcement
NSF	National Science Foundation
OCP	Office of Commercial Programs
OSSA	Office of Space Science and Applications
PI	Priciple Investigator
R&D	Research and Development
SAAC	Space Applications Advisory Committee
SAMS	Space Acceleration Monitoring System
SL-D1	First German Spacelab
SL-D2	Second German Spacelab
SL-J	Japanese Spacelab
SPAR	Space Processing Applications Rocket
SS	Space Station
STS	Space Transportation System or Shuttle Transportation System
SQUIDs	Superconducting quantum interface detectors
UCSD	University of California, San Diego
USML	United States Microgravity Laboratory
USRA	Universities Space Research Association

⑬

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

JUL 6 1988

Reply to Attn of: XC:BC:drg

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

RECEIVED
JUL - 7 1988

Dear Mr. Chairman:

In the Committee Report 100-204 accompanying the bill (H.R. 2782) to authorize FY 1988 appropriations to the National Aeronautics and Space Administration (NASA), NASA was requested to develop a plan providing for an Explorer program baseline of one flight per year.

I am pleased to submit a report in response to the request of the Committee. The report reviews briefly the past and current NASA Explorer program, the concerns of the U.S. scientific community about the program, and the steps planned by NASA to address the concerns.

If you have any questions about the report please call Ms. Barbara Cherry of my office on 453-1055.

Sincerely,

Jon A. McBride
Assistant Administrator
for Congressional Relations

Enclosure

cc: Honorable Manuel Lujan, Jr.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)
OFFICE OF SPACE SCIENCE AND APPLICATIONS (OSSA)

REPORT ON

EXPLORER FLIGHT OPPORTUNITIES

SUBMITTED TO THE U.S. HOUSE OF REPRESENTATIVES'
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

JUNE 1988

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PREFACE

The budget report, submitted by the U.S. House of Representatives' Committee on Science, Space, and Technology to accompany the National Aeronautics and Space Administration (NASA) Authorization Act for Fiscal Year 1988, cited the Committee's continuing concern regarding the adequacy of flight opportunities for small- and medium-class science payloads. The Committee requested that NASA submit a report describing the funding requirements and management initiatives necessary to provide one Explorer flight per year.

This report has been prepared in response to the Committee's request. It provides a brief overview of the NASA Explorer program to date and describes some of the benefits that have accrued from the program. The current Explorer program is described, the reaction of the community to current circumstances within the program is discussed, and the steps planned by NASA to adress community concerns are presented. A detailed history of the NASA Explorer program is presented as an Appendix to this report.

The report "The Crisis in Space and Earth Science," prepared by the NASA Space and Earth Science Advisory Committee, reports by the National Academy of Sciences' Space Science Board entitled "The Explorer Program for Astronomy and Astrophysics" and "A Strategy for the Explorer Program for Solar and Space Physics," and the Office of Space Science and Applications Strategic Plan have been drawn upon freely in preparing this response.

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INTRODUCTION AND SUMMARY

Explorer spacecraft have long been used as an inexpensive means to explore the Earth's atmosphere, ionosphere, and radiation belts; to study the Sun and the solar wind; and to survey cosmic objects in new spectral regions that are inaccessible from the Earth's surface. Explorer spacecraft have served frequently both to open up new fields of space science and to investigate in detail unique and particular aspects of science. The spectrum of Explorer missions has ranged from relatively simple spinning spacecraft measuring the particles and fields in the space environment, to stabilized platforms with sophisticated pointing and control systems carrying atmospheric and astrophysical payloads. Scientific investigations, carried out on Explorer spacecraft, have similarly ranged in complexity from instruments built and operated by individual Principal Investigators to facility-class experiments used by guest observers.

About 70 Explorer spacecraft have been launched since the program began with Explorer 1 in 1958. These missions have had an enormous impact on the course of science in the United States (U.S.). The Explorer program has also been a primary tool in the development of civilian space programs throughout the World. Virtually every country in Western Europe, that now has a space program, began its program with cooperative Explorer missions. The same is true of Canada. Thirty-two such cooperative international space missions have been carried out under the auspices of the Explorer program. Table I lists the successful Explorer missions launched between 1958 and 1988 together with the Explorers currently under development. A complete list of successful Explorer cooperative programs is provided in Table II.

The Explorer program continues today to offer the U.S. space science communities a range of opportunities for flight activities. The largest, and generally most sophisticated Explorers, are the Delta-class missions. These missions are, as their name implies, launched by Delta-class expendable launch vehicles (ELV). Explorers in this category typically cost somewhere in the range $50 million to $150 million for the development of both the spacecraft and the instrument payload. The Delta-class missions also now include Explorer Platform payloads carried by the Shuttle for replacement in orbit.

Smaller than the Delta-class Explorers, are the Scout-class missions, which NASA seeks to reintroduce in 1989. These are characterized by spacecraft traditionally launched by the Scout-class ELV's and by spacecraft and instrument development costs that are typically $30 million or less. The third category of current Explorer opportunities are the "missions of opportunity." These are characterized by the provision, by U.S. investigators, of an instrument or a part of a payload for flight on a mission belonging to another country or agency. These opportunities may arise from situations external to NASA. Explorer program costs for a mission of opportunity payload are, typically, less than $20 million. The overall yearly budget allocated to such missions of opportunity is constrained to be approximately 15% of the total Explorer program budget.

NASA's primary objective for the Explorer program is to provide a sustained program of space science missions that embodies the following characteristics:

1. a modestly scaled option for scientific research,
2. a quick response to new scientific opportunities,
3. an extended observing period,
4. access to regions of space optimum for the particular observations,
5. hands-on experience for university researchers and students,
6. complementarity and extension of the science of major missions through highly focussed studies,
7. international collaborations, and
8. a first step to define and guide the requirements for major missions through exploratory studies and proof of concept flights.

The combined effects of inflation, the maturing of the scientific fields that use the Explorers, the resulting increased demand on instrument and spacecraft performance, and, most recently, the Challenger accident, have had a profound effect on realizing this objective. Only one small Explorer mission has been launched since 1984, the Italian San Marco cooperative mission. A program that once had as many as 3 to 6 missions launched per year has had 6 missions launched between 1979 and 1987.

The U.S. scientific community, which is the prime user of the Explorer flight opportunities, has become increasingly concerned as the flight rate declined. The National Academy of Sciences (NAS) and the NASA Space and Earth Science Advisory Committee (SESAC) have both undertaken detailed studies that recommended several management initiatives for NASA's consideration. The NAS also concluded that the Explorer program requires an annual funding level of $130 million to achieve the goal of one Explorer mission per year.

The remainder of this report describes the current Explorer program, academic and foreign benefits of the program, the crisis identified by the U.S. scientific and applications communities, and NASA's actions and plans to rectify the current situation. A history of the entire U.S. Explorer program, from Explorer 1 to the present day, is provided as Appendix A.

TABLE IA. SUCCESSFUL EXPLORER MISSIONS
1958-1988

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
1958			
Explorer 1	1 February	Jupiter C	Energetic particles. Discovered Van Allen Belt.
Explorer 3	26 March	Jupiter C	Instrumentation similar to Explorer 1. Carried small tape recorder.
Explorer 4	26 July	Jupiter C	Spatial study of orbital radiation belts, particularly from Argus nuclear weapon test.
1959			
Explorer 6	7 August	Thor-Able	First photograph of Earth from space. Measured electric ring current circling Earth.
Explorer 7	13 October	Juno II	Data on radiation belts, magnetic storms, cosmic rays, micrometerites, and ionospheric composition.
1960			
Explorer 8	3 November	Juno II	Ionosphere composition. Confirmed helium layer in upper atmosphere.

TABLE IA. SUCCESSFUL EXPLORER MISSIONS
1958-1988

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
1961			
Explorer 9	16 February	Scout	Determined Air density by measuring drag on inflatable sphere.
Explorer 10	25 March	Thor-Delta	Terrestrial and interplanetary magnetic field measurements and effects of solar flares on these fields.
Explorer 11	27 April	Juno II	Gamma-Ray astronomy-eliminated simultaneous matter-antimatter creation theory of steady-state cosmology.
Explorer 12	16 August	Thor-Delta	Observed trapped particles and magnetic fields. Identified Van Allen Belt as a part of the magnetosphere.
1962			
Explorer 14	2 October	Thor-Delta	Continuation of Explorer 12 particles and fields observations.
Explorer 15	27 October	Thor-Delta	Detailed measurement of Starfish Artificial radiation belts.
Explorer 16	16 December	Scout	First statistical sample of micrometeoroid flux.
1963			
Explorer 17	2 April	Thor-Delta	Diurnal and spatial variation of ionospheric temperature and electron density. Discovered belt of neutral helium around Earth.

TABLE IA. SUCCESSFUL EXPLORER MISSIONS
1958-1988

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
Explorer 18 (IMP-A)	26 November	Thor-Delta	Radiation environment in cislunar space. Confirmed solar wind shock wave on magnetosphere.
Explorer 19	19 December	Scout	Air density as a function of latitude by measuring drag on an inflatable sphere.
1964			
Explorer 20	25 August	Scout	Ionospheric Explorer—measurement of electron density distribution in F_2 layer.
Explorer 21 (IMP-B)	4 October	Thor-Delta	Measure particles and fields environment in cislunar space and gather data to develop solar flare prediction capability for Apollo.
Explorer 22	10 October	Scout	Beacon Explorer—measurement of total electron content of ionosphere.
Explorer 23	6 November	Scout	Micrometeoroid penetration of materials and test of micrometeroid detectors for the Pegasus satellites.
Explorer 24 (Air Density)	21 November	Scout	Comparison of charge particle energy injection with atmospheric temperature and density.
Explorer 25 (Injun)			Dual launch with Explorer 24.

TABLE IA. SUCCESSFUL EXPLORER MISSIONS
1958-1988

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
Explorer 26	21 December	Thor-Delta	Study of injection, trapping, and loss mechanisms of naturally and artificially trapped radiation.
1965			
Explorer 27	29 April	Scout	Beacon Explorer—doppler tracking of orbital perturbation to measure Earth's gravitational field and electron density in the ionosphere.
Explorer 28 (IMP-C)	29 May	Thor-Delta	Measurement of the magnetospheric boundary and cislunar environment.
Explorer 29 (GEOS-A)	6 November	Thor-Delta	Map the Earth's gravitational field, correlate geodetic datums to improve world-wide geodetic datum accuracies
Explorer 30	19 November	Scout	Monitor solar X-ray and ultraviolet emissions and correlate with ground based optical and radio observations.
Explorer 31	29 November	Thor-Delta	Dual launch correlation of ionosphere composition and electron density. (Canadian Co-op)
1966			
Explorer 32	25 May	Thor-Delta	Helium and hydrogen ion distribution in the exosphere.
Explorer 33 (IMP-D)	1 July	Thor-Delta	Measure the particles and fields environment in lunar orbit and the distant magnetic tail of the Earth.

TABLE IA. SUCCESSFUL EXPLORER MISSIONS
1958-1988

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
1967			
Explorer 34 (IMP-F)	24 May	Thor-Delta	Investigated the region between the Earth's magnetosheath and shock front. Solar charged particle propagation studies.
Explorer 35 (IMP-E)	19 July	Thor-Delta	Lunar anchored orbit. Particles and fields environment of the moon, interplanetary field and plasma observations between Earth and moon.
1968			
Explorer 36 (GEOS-B)	11 January	Delta	Geometric and gravimetric geodetic measurements.
Explorer 37 (SOLRAD-9)	5 March	Scout	Monitor of solar X-ray emissions and time history, and provide real time solar data to scientific community (NASA/NRL).
Explorer 38 (RAE-A)	4 July	Thor-Delta	Observed strong, sporadic radio bursts from Jupiter and monitored low-frequency radio emissions from cosmic sources, the sun, and the Earth.
Explorer 39 (Air Density) Explorer 40 (Injun)	8 August	Scout	Density and radiation characteristics of upper atmosphere. Dual launch.

TABLE IA. SUCCESSFUL EXPLORER MISSIONS
1958-1988

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
1969			
Explorer 41 (IMP-G)	21 June	Thor-Delta	Particles and fields measurements in cislunar space during high solar activity.
1970			
Explorer 42 (SAS-A) (Uhuru)	12 December	Scout	First x-ray astronomy survey of celestial X-ray sources (2-20Kev).
1971			
Explorer 43 (IMP-I)	13 March	Delta	Solar wind/interplanetary magnetic field relationships. First observation of quiet time interplanetary electrons.
Explorer 44 (SOLRAD 10)	8 July	Scout	X-ray and UV study of Sun (NRL/NASA).
Explorer 45 (SSS-A)	15 November	Scout	Studied Earth's ring current and development of the main phase of magnetic storms.
1972			
Explorer 46	13 August	Scout	Meteoroid Technology Satellite. Provided data on meteoriod speeds, quantity and penetration rates.

TABLE IA. SUCCESSFUL EXPLORER MISSIONS
1958-1988

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
Explorer 47 (IMP-H)	22 September	Delta	Cislunar radiation environment; spectra and intensity of cosmic rays; and information on interplanetary electric and magnetic fields.
Explorer 48 (SAS-B)	15 November	Scout	Sky survey of high energy gamma radiation from the celestial sphere.
1973			
Explorer 49 (RAE-B)	10 June	Delta	Radio astronomy—galactic and solar radio noise measurements.
Explorer 50 (IMP-J)	25 October	Delta	Interplanetary radiation environment. Mapped the Earth's magnetotail.
Explorer 51 (AE-C)	16 December	Delta	Solar UV absorption/photochemical processes in the atmosphere.
1974			
Explorer 52 (Hawkeye)	3 June	Scout	Study of magnetosphere in vicinity of neutral point.
1975			
Explorer 53 (SAS-C)	7 May	Scout	Catalog X-ray emissions from extra-galatic sources and positions and variablity of galatic and extra-galatic X-ray sources.

TABLE IA. SUCCESSFUL EXPLORER MISSIONS
1958-1988

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
Explorer 54 (AE-D)	6 October	Delta	Study of chemical processes and energy transfer in the atmosphere. Understanding of heat balance processes in the atmosphere.
Explorer 55 (AE-E)	20 November	Delta	Study of chemical processes and energy transfer in the atmosphere. Measurement of ozone depletion from man-made causes.
1976			
None			
1977			
ISEE-1	22 October	Delta	With ISEE-2 resolved ambiguities associated with the motion of near-Earth plasma and field boundaries.
ISEE-2			Dual launch with ISEE-1 (ESA/US).
1978			
IUE	26 January	Delta	Obtain high resolution ultraviolet spectra of stars and planets. IUE data has determined fundemental characteristics of interstellar and intergalactic matter. (ESA/US)
ISEE-3	12 August	Delta	Investigated solar wind and its interaction with the magnetosphere (ESA/US).

TABLE IA. SUCCESSFUL EXPLORER MISSIONS
1958-1988

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
1979			
None			
1980			
None			
1981			
Dynamics Explorer (A & B)	19 February	Delta	Coordinated dual spacecraft studies of electric and fields and plasmas responsible for electromagnetic phenomena in the magnetosphere.
SME	6 October	Delta	Solar Mesosphere Explorer: Solar input to the upper atmosphere, particularly changes in the ozone content of the mesosphere.
1982			
None			
1983			
IRAS	25 January	Delta	Infrared Astronomy Satellite—Catalog of 245,000 IR sources, co-op with Netherlands and UK.

TABLE IA. SUCCESSFUL EXPLORER MISSIONS
1958-1988

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
1984			
AMPTE	16 August	Delta	Active Magnetospheric Particle Tracer Explorer—Mass transfer from solar wind into magnetosphere, co-op with Germany and UK.
1985			
None			
1986			
None			
1987			
None			
1988			
San Marco - D	25 March	Scout	Density of the neutral atmosphere, equatorial airglow, and solar extreme ultraviolet, co-op with Italy.

TABLE IB. APPROVED EXPLORER MISSIONS *
1988 - 1993

NAME/ DESIGNATION	LAUNCH DATE	VEHICLE	MISSION SUMMARY
1989			
COBE	TBD	Delta	Cosmic Background explorer—Cosmology: the universe at large redshifts.
1990			
None			
1991			
EUVE	TBD	Delta	Extreme Ultraviolet Explorer—Whole sky survey for extreme ultraviolet sources. Payload developed at University of California. First use of the Explorer Platform.
1992			
None			
1993			
XTE	TBD		X-ray Timing Explorer—Study variable X-ray sources, such as neutron stars and black holes. To be integrated onto Explorer platform in space.

* Excluding missions of opportunity on foreign or DoD spacecraft.

TABLE II. COOPERATIVE EXPLORER MISSIONS

LAUNCH DATE	COOPERATING NATION OR ORGANIZATION PROGRAM/SPACECRAFT	LAUNCH VEHICLE
	UNITED KINGDOM	
26 April 1962	Ariel-I	Delta
27 March 1964	Ariel-II	Scout
29 November 1965	DME-A	Thor-Agena
5 May 1967	Ariel-III	Scout
11 December 1971	Ariel-IV	Scout
15 October 1974	UK-5	Scout
2 June 1979	UK-6	Scout
25 January 1983	IRAS	Delta
16 August 1984	AMPTE	Delta
	CANADA	
29 September 1962	Alouette-I	Thor-Agena
29 November 1965	Alouette-II	Thor-Agena
30 January 1969	ISIS-I	Delta
31 March 1971	ISIS-II	Delta
	ITALY	
15 December 1964	San Marco-A	Scout
26 April 1967	San Marco-B	Scout
12 December 1970	Explorer 42	Scout
24 April 1971	San Marco-C1	Scout
15 November 1971	Explorer 45	Scout
16 November 1972	Explorer 48	Scout
18 February 1974	San Marco-C2	Scout
7 May 1975	Explorer 53	Scout
25 March 1988	San Marco - D	Scout

TABLE II. COOPERATIVE EXPLORER MISSIONS

LAUNCH DATE	COOPERATING NATION OR ORGANIZATION PROGRAM/SPACECRAFT	LAUNCH VEHICLE
	FRANCE	
6 December 1965	French IA	Scout
	FEDERAL REPUBLIC OF GERMANY	
8 November 1969	AZUR-1 (GRS-A)	Scout
20 September 1971	Barium Ion Cloud (GRS-B)	Scout
16 December 1972	AEROS-A2	Scout
16 July 1974	AEROS 2	Scout
16 August 1984	AMPTE	Delta
	NETHERLANDS	
27 August 1974	ANS-A	Scout
25 January 1983	IRAS	Delta
	EUROPEAN SPACE AGENCY	
17 May 1968	ESRO IIB (IRIS)	Scout
3 October 1968	ESRO IA (Aurorae)	Scout
22 October 1977	ISEE	Delta
26 January 1978	IUE	Delta

THE CURRENT EXPLORER PROGRAM

In the current Explorer program, seven "missions" are approved for development and launch between 1988 and 1993. These are the Cosmic Background Explorer (COBE), the German Roentgen Satellite (ROSAT), the Extreme Ultraviolet Explorer (EUVE), the NASA/Department of Defense (DoD) Combined Release and Radiation Effects Satellite (CRRES), the Japanese Solar-A mission, the X-Ray Timing Explorer (XTE), and the Japanese Astro-D mission. Only three of these missions, COBE, EUVE, and XTE are major, Delta-class Explorer missions carrying U.S. science payloads. All of the others are missions of opportunity in which NASA has been given the opportunity to participate in missions sponsored by other nations, or, in the case of CRRES, other agencies.

Cosmic Background Explorer (COBE)

COBE, which will be launched on a Delta rocket in 1989, is designed to make a substantial improvement in our knowledge of the condition in the universe at very early times in its evolution. The focus of the mission is to study the spectrum, intensity, and isotropy of the primeval cosmic background radiation at wavelengths longer than that of the 3 degree K black-body radiation maximum, and to detect or set stringent limits on the universal radiation energy density at shorter wavelengths. This is radiation emanating from distant sources but at later times than the primeval fireball.

The mission will provide (a) freedom from atmospheric opacity, emission, and fluctuations in the emission; (b) full sky coverage with a single complement of instruments; (c) a benign and controlled thermal environment to reduce systematic errors; (d) the ability to perform absolute primary calibration in flight without the necessity of windows to avoid condensation on calibrators and instruments; and (e) sufficient time both to perform tests for systematic errors and to gain the increase in sensitivity permitted by the extended observing time.

COBE will map the spectrum and the angular distribution of diffuse radiation from the universe over the entire wavelength range from 1 μ to 1 cm. It will carry three instruments: a set of Differential Microwave Radiometers, operating at 31.4, 53, and 90 GHz (1, 0.6, 0.3 cm respectively); a Far Infrared Absolute Spectrophotometer, covering 1 to 0.01 cm; and a Diffuse Infrared Background Experiment, covering 1 to 300 μ. These instruments will use the ideal space environment, a one-year lifetime, and standard instrument techniques to achieve orders-of-magnitude improvements in sensitivity and accuracy, providing a fundamental data base for cosmology. The data from all three experiments will be analyzed together to distinguish nearby sources of radiation from the cosmologically interesting diffuse background radiations.

Roentgen Satellite (ROSAT)

The inclusion of the U.S.-provided high-resolution X-ray imaging detector on the Federal Republic of Germany's Roentgen Satellite (ROSAT) provides an important extension of the ROSAT's X-ray telescope capability, allowing the full angular resolution of this telescope to be realized. The ROSAT will be launched on a Delta rocket in early 1990. Participation in the ROSAT program will provide an opportunity for the U.S. astronomical community to obtain X-ray imaging data in the 12- to 15-year gap between the High Energy Astronomy Observatory -2 (Einstein) mission and the Advanced X-Ray Astrophysics Facility (AXAF). The U.S.-developed High Resolution Imager and the German-built position-sensitive proportional counter together with the 0.8 meter diameter X-ray mirror represent significant improvements in sensitivity over the comparable instruments on Einstein, but cover a narrower energy band. These imaging detectors can be used to carry out studies of the X-ray emission from stellar coronae, globular clusters, supernova remnants, normal galaxies, active galactic nuclei and quasars, and clusters of galaxies. Community-wide access to both of these instruments will be possible through a guest observer program.

Extreme Ultraviolet Explorer (EUVE)

The EUVE will survey the whole sky in several filter pass-bands between 80 and 900 Å. The payload also includes three spectrometers which will be used to carry out spectroscopic observations of bright sources: the bandpass covered is 80-700 Å, with a resolving power of $\lambda / \Delta \lambda = 100$. Until recently, the extreme ultraviolet spectral range was presumed to be of limited interest because the interstellar medium was expected to block passage of radiation in these wavelengths. However, recent discoveries have shown that the very local interstellar medium is partially ionized, and that the density of neutral species is quite low in some directions. This low density extends for considerable distances and the interstellar medium, in general, is very patchy.

A number of stellar objects were detected at extreme ultraviolet wavelengths by an experiment on the Apollo-Soyuz mission, by subsequent rocket experiments, by the Voyager spacecraft, and by the European X-Ray Astronomy Satellite (EXOSAT) mission. Hot white dwarfs, cool stars, binary systems, cataclysmic variables, some planets, the interstellar medium, and some extragalactic sources, should all be observable by EUVE. The EUVE spectrometer will be available to astronomers on a guest observer basis. EUVE will be the first user of the Explorer platform, which is discussed under Management Initiatives. It will be launched on a Delta rocket in 1991.

Combined Release and Radiation Effects Satellite (CRRES)

The CRRES is a joint NASA/DoD satellite which will be launched by an Atlas Centaur in June 1990. The mission will be in two phases: a Low Earth Orbit (LEO) phase and a Geosynchronous Transfer Orbit (GTO) phase. During both phases, CRRES will be collecting new data on the dynamics, structure, and chemistry of the near-Earth space environment. It will also conduct studies of electronics survivability which will be complemented by parallel ground exposure tests. CRRES will carry a complement of chemicals for release in the ionosphere for active probing experiments and an instrument payload to collect scientific data on charged particles, electric and magnetic fields, and waves. The chemical releases will function both as tracers to illuminate physical phenomena and as active experiments to produce specific perturbations which will be studied both by instruments on CRRES and by ground- and aircraft-based observatories.

NASA's primary contribution to the CRRES mission is the design and development of the twenty-four chemical release canisters and the management of the mission during the LEO phase when the chemicals are released. The U.S. Air Force Space Test Program is responsible for the satellite development, the development of the remaining elements of the scientific payload, the launch, and for mission operations during the GTO phase of the program.

Solar-A

The Solar-A/Soft X-ray Telescope (SXT) is a collaborative program between the Japanese Institute of Space and Aeronautical Sciences (ISAS) and NASA for the high energy observation of solar flares. The precedent for this cooperation was set by collaborative solar flare studies conducted by the U.S. Solar Maximum Mission and the Japanses HINOTORI mission. The complementary nature of these two spacecraft facilitated joint research into solar activity through collaborative observations, data exchange, and discussions in workshops, seminars, and symposia. Based on the success of this collaboration, the Japanese invited NASA to provide an X-ray investigation for the planned ISAS High Energy Solar Physics (HESP) mission, now known as Solar-A. The competitively selected U.S. contribution is a Soft X-Ray Telescope (SXT).

The Solar-A mission will be launched in 1991, and will conduct follow-on investigations of flares and other manifestations of solar activity at the peak of the current solar cycle. It will be the only mission making such measurement at this time.

X-Ray Timing Explorer (XTE)

XTE, to be launched in 1993, will be devoted to temporal studies and to broadband spectroscopy of compact X-ray sources over the energy range 1 to 200 keV. The mission is being designed as a complement to the Advanced X-Ray Astrophysics Facility (AXAF) which will be able to obtain X-ray images of the sky with far higher spatial resolution than the XTE but will not have the time resolution or energy range of the Explorer mission.

The XTE experiments will feature a large photon collection area and an all-sky pointing capability with a complement of three instruments: a 1-m^2 effective-area xenon proportional counter array, an all-sky monitor, and an array of high-energy detectors with a total effective-area of 2000 cm^2.

Previous studies of compact X-ray sources, based upon relatively brief observations with detectors of modest area, have proven to be scientifically very rich. The results point directly to fruitful studies possible with XTE, especially concerning neutron stars and black holes. For neutron stars, XTE will determine the orbits and the masses of neutron stars, variations in spin rates of the accreting pulsars, phenomena associated with the intense magnetic fields of X-ray pulsars, and X-ray bursts from unstable thermonuclear burning of accreted material.

In its search for evidence of black holes, XTE will explore the intensity and spectral variations due to accretion instabilities as matter approaches a black hole. Interest in rapid temporal variations has been greatly enhanced by the recent exciting discovery, with the European mission EXOSAT, of oscillations on timescales of tens of milliseconds from a number of X-ray sources. XTE will also conduct indepth temporal and broad-band spectral studies of X-ray nova and other transient phenomena, white dwarf stars, and instabilities in the X-ray producing gas orbiting white dwarfs, neutron stars, and black holes. The temporal variability of bright active galactic nuclei is also amenable to study with XTE. In addition to current areas of X-ray timing research, XTE will also permit studies of qualitatively new phenomena on the shortest timescales. For the study of aperiodic phenomena, an increase in collecting area provides a fundamental advantage that cannot be obtained through longer observations. The entire XTE observing program will be dedicated to guest observers, selected through competitive proposals.

Astro-D

Astro-D is the fourth Japanese (ISAS) X-ray astronomy satellite, following Hakucho, Tenma, and Ginga. It is planned to be a high-sensitivity X-ray observatory, comparable to the U.S. Einstein observatory, but with much higher spectral resolution over a wider energy range. The Astro-D spacecraft, which will be launched in 1993, will carry a four element, multinested, thin foil telescope feeding a number of focal plane detectors, including imaging gas scintillation proportional counters and charge coupled devices (CCD's). U.S. involvement in the Astro-D mission primarily involves collaborations in the development of the conical foil X-ray telescopes and the CCD cameras. U.S. scientists will also share in Astro-D science operations and data analysis.

The scientific objectives of the mission include spectroscopic studies of active galactic nuclei, determination of the temperature and abundance structure of clusters of galaxies, observations of the cosmic X-ray background, spectroscopic studies of galactic sources, measurements of the temperature and abundance structure of supernova remnants, and discovery of new sources. Astro-D will be launched into a low-inclination, low-Earth, orbit by an ISAS launch vehicle and will have a mission lifetime of at least two years.

NATIONAL BENEFITS FROM THE EXPLORER PROGRAM

In addition to scientific productivity, two aspects of the Explorer program that are frequently overlooked are their contributions to U.S. academic programs and their contributions to U.S. foreign policy.

A Tool for Academic Excellence

The early Explorer program was particularly conducive to academic research and training. A student could have hands-on experience in the development of an instrument, and in certain cases, hands-on experience in the development, test, and/or operation of the spacecraft itself. Explorers offered students the entire spectrum of learning opportunities required for participation in much larger projects, i.e., mission planning, integration, development, launch, mission operations, data analysis, and scientific interpretation.

The experience was valuable, not only in the development of future space scientists, but also in the development of experimental scientists, spacecraft engineers, and program managers. The Explorer program has proved many times that persons who participate in the development of a space instrument gain the direct experience necessary to qualify them for a broad spectrum of other senior scientific, technical, and managerial positions. Universities such as the University of Iowa, University of Chicago, Massachusetts Institute of Technology, University of Texas, University of California, University of Colorado, and many others, have made immeasurable contributions to the intellectual and technical strength of this country through their Explorer-trained students.

In addition to the hands-on opportunity for students to develop their skills, the Explorer program has offered a continuity of high quality research opportunities such that a student and professor could be assured that: a) the student would complete his or her thesis research in a reasonable period of time, b) that the research was valuable and was recognized in the community as front-line science, and c) that participation in the Explorer program offered an opportunity to become associated with other dedicated and talented persons.

A Tool for Foreign Policy

The other, frequently overlooked, aspect of the Explorer program has been its role in international scientific cooperation. Virtually every Western European nation that has developed a space program began its program with a cooperative Explorer mission. The same is true of Canada.

Great Britain was the first nation to initiate a cooperative space program with NASA. The first United Kingdom (U.K.) Explorer, Ariel I, was launched in 1962. This was followed by three additional Ariel missions and by two astronomy and cosmic ray missions, called U.K.-5 and -6. The U.K. also played a major role in the Direct Measurement Explorer. In addition, Canada, France, Germany, Italy, and The Netherlands, as well as the European Space Agency (ESA), all participated actively with cooperative Explorer missions. Table II lists these missions.

Foreign policy was, by no means, the sole motivation for these missions. Before NASA accepted a proposal for a cooperative mission, the proposal was carefully reviewed to assure that the scientific objectives of the mission were first class and that the mission offered good opportunities for U.S. scientists to collaborate on the development of flight hardware and to gain access to the resulting scientific data. Many of the cooperative Explorer missions, such as the U.S./Netherlands/U.K. cooperative Infrared Astronomy Satellite (IRAS), have become outstanding scientific successes that continue to receive scientific accolades years after they cease to operate.

Interest in scientific collaboration among foreign countries has remained strong. Currently, agreements exist for U.S. participation in the German X-ray astronomy mission, ROSAT, and in the Japanese Solar-A and Astro-D missions. Since the foreign countries are assuming the lead role in these missions, and the U.S. participation is primarily limited to the development of science instruments and to science operations and data analysis activities, these programs fall into the category of "missions of opportunity."

The Explorer program, because of its flexibility, lends itself particularly well to such missions of opportunity. Foreign governments that invite NASA to participate on one of their missions are frequently relatively advanced in their mission planning. Consequently, it would be difficult or impossible for NASA to proceed through its traditional new start approval cycle for the U.S. contribution and still remain in phase with the host nation's schedule. Because most of these missions involve a relatively small commitment of U.S. funds, they can be accommodated within the Explorer program without displacing an already approved U.S. Explorer mission. Thus, a decision to participate in the cooperative program can be made on a time scale that is compatible with the schedule of the proposing foreign government. This approach to missions of opportunity is strongly endorsed by the scientific community.

THE SCIENCE COMMUNITY'S VIEW OF THE EXPLORER PROGRAM

The U.S. scientific community has been particularly concerned over the recent decrease of Explorer flight opportunities. Committees of both the Space Science Board and the NASA Advisory Council recently studied the Explorer program. While reaffirming the strong support for the program, these studies also recommended major increases in funding and number of flight opportunities. For example, the Space Science Board Committee on Space Astronomy and Astrophysics (CSAA) report, "The Explorer Program for Astronomy and Astrophysics," begins with the statement:

"In its first 25 years the Explorer Program has produced an outstanding record of discoveries that impact nearly all aspects of the scientific study of the Universe."

However, the Chairman of the National Academy of Sciences, Space Science Board, Dr. Thomas M. Donahue, in his foreword to the CSAA report, also comments that:

> "The great strengths of the Explorer Program— easy, frequent, and inexpensive access to space—have not been fully exploited in recent years......
> They (Explorers)will continue to be the primary tool for exploring new regions or phenomena, a means of demonstrating new design concepts and hardware for scientific instruments."

The NASA Advisory Council's Space and Earth Science Advisory Committee (SESAC) in its report "The Crisis in Space and Earth Science" calls attention to the problems caused by a continuously growing family of space and Earth science communities. As new disciplines recognize the benefits of space observations, they bring new researchers to the Explorer program. At the same time, the established space sciences communities continue to find challenging new scientific questions to motivate their research. The maturing of established scientific disciplines and the growth of new disciplines have placed demands on the Explorer program for increased flight opportunities, increased instrument capability, higher data rates, better pointing accuracy and stability, and data reception from many different regions of space. Further, as scientists recognize that flight opportunities are becoming less frequent, they exert pressure to make each mission more capable. Instruments are becoming more sophisticated and spacecraft payloads more extensive than would have been the case had the scientific community had the assurance of frequent flight opportunities. The situation has been exacerbated by the fact that the primary launch vehicle, the Space Shuttle, can easily accommodate the launch requirements of these more capable missions.

The increases in mission costs caused by these demands, coupled with the uncompensated impact of inflation on the Explorer program, have resulted in long delays and mission descopings that have demoralized the scientific community. Twenty-four Explorers were successfully launched in the decade from 1966 through 1975 (Table I). Only ten Explorers have been launched since 1976.

Progress in science is dependent upon the involvement of talented, dedicated people driven to satisfy their curiosity about nature. Dedication alone, however, is not enough. In order to learn, aspiring young scientists must have the opportunity to experiment and to obtain timely results from their experiments. They must have the support of a strong educational system that gives them the opportunity to work with established researchers on substantive scientific questions. The educational institutions supporting this research must believe in the timely implemention, long-term health, and continuity of the program in order to make the necessary investments in faculty and facilities. Healthy science must have goals and opportunities that are perceived to be exciting and important by all parties: the students, the specialists in the field, the institutions, and the public at large. A Explorer program is needed to capitalize on the wealth of intellectual energy and technical talent present in U.S. research institutions.

MANAGEMENT INITIATIVES

Introduction

Explorers, even in an era of the Space Station, will continue to be a primary tool for exploring new regions of space or new phenomena. They will provide a means of demonstrating new design concepts and scientific instruments, and they will be the bridge to major new missions. Explorers can provide the avenue to develop the research and engineering capabilities of individuals and organizations. Because Explorers can be placed into unique orbits, they provide the ability for small multispacecraft missions to make direct measurements throughout large volumes of otherwise difficult to reach space. Explorers also meet the moderately demanding spacecraft pointing and stabilization requirements of many of the user communities.

Congress recognized the gravity of the Explorer program and has augmented the Explorer budget. Scientific advisory committees state that to meet the scientific and technological needs of the space science disciplines using the Explorers, a minimum of one new Explorer opportunity per year is required.

NASA, to assure the optimum use of these funds, is implementing several new management initiatives. The goal of these initiatives is to again achieve the flight frequency of one Explorer launch per year. The first initiative emphasizes small Explorer missions. This effort will capitalize on the combination of the lifting ability of the low cost Scout-class launch vehicle and the light weight instrumentation that is adequate for many excellent, but simple, scientific investigations. The second initiative is directed toward a better understanding of mission requirements by bringing the scientific community into the conceptual planning process of a mission such that the mission requirements can influence mission design. The next initiative, the Explorer Platform, is based on the use of the multimission modular (MMS) spacecraft . The Explorer Platform is a flexible, serviceable spacecraft that can have its payload replaced in space. Two Explorer missions are already approved for flight on the Explorer Platform. The final major initiative is directed towards a more systematic exploitation of missions of opportunity. Better liaison will be established with working level counterparts in foreign space agencies and other U.S. agencies. With closer ties between the scientific discipline chiefs in NASA and in other space agencies, NASA will be able to identify opportunities for U.S. scientists on non-NASA missions earlier and to plan and organize U.S. scientific participation in a more systematic and equitable manner.

Scout-Class Explorers

As a first step in the restoration of small Explorer spacecraft, NASA has prepared an Announcement of Opportunity (AO) that invites proposals for Scout-class Explorer missions. These small missions are intended to provide quick implementation of scientific opportunities for space science investigations, prove new scientific concepts, and make other significant contributions to space science. The scope of the missions is expected to be such that a single Principal Investigator will have responsibility for an individual mission. The President's FY 1989 budget has requested funds to enable NASA to proceed with this initiative.

The Scout-class rocket can lift a total payload mass of about 200 kg. Such a spacecraft can provide 25 to 100 watts of power, depending on the spacecraft orbit and pointing requirements, and can support a data rate of up to 10 kilobits per second. Launch facilities for the current Scout launch vehicle exist at the NASA Wallops Flight Facility, Virginia; Vandenberg Air Force Base, California; and the San Marco Platform, Kenya.

The Scout-class Explorer missions are intended to facilitate rapid execution of scientific investigations in less than 3 years from the time of selection of the investigation for the detailed design and hardware development phases of the mission. Faster reaction times can be achieved through use of mature instrumentation. Costs of the missions are not expected to exceed approximately $30million in Fiscal Year 1987 dollars. The plan is to implement one or two new missions per year, and to start the development of the first mission in FY 1989, directed toward a launch in 1991.

Scout-class Explorer missions are particularly attractive to the academic community in that the missions again give universities the opportunity to bring students and young professors into the actual hands-on development of the mission and in its operation. A strong and continuing Scout-class Explorer program will reinstate the close ties of U.S. universities to the space sciences program, and it will provide the participatory learning environment that is so important to gaining a real understanding of the science, technology, and project management required to conduct a scientific experiment in space.

The AO will request proposals in the traditional Explorer disciplines of astrophysics, solar physics, space plasma and cosmic ray physics, and upper atmosphere science. U.S. proposers responding to the AO can propose a mission that uses a new spacecraft design that is uniquely configured to their investigation, or they can propose to use an existing or planned Scout-class spacecraft. For programmatic or technical reasons, NASA may provide a spacecraft other than that described in the proposals.

NASA has been approached by several foreign space agencies who are also interested in small, cooperative missions. Because of this interest and potential benefit to the U.S., proposals for bilateral participation will be accepted under the AO. Two different modes of cooperation are available. In the first mode, proposals will be accepted from Principal Investigators from U.S. institutions that involve non-U.S. participants. U.S. investigators, who propose missions involving international participation, must indicate in their proposals the division of responsibility between NASA and the other partners. In the second mode, foreign governments may submit proposals for bilateral missions, executed under international agreements. In such a joint mission, it is envisioned that the foreign partner will provide the spacecraft and mission integration, with instruments provided by both the U.S. and the foreign partner. NASA will provide launch services. Operations support, data sharing, etc., will be negotiated on a case by case basis.

Explorer Concept Study

NASA's second management initiative is to streamline the Explorer design and development process. Rather than allowing a greater number of Explorers to be designed than can be accommodated within the Explorer development budget, and involving the scientific community in mission prioritization after the studies are complete, NASA will now involve the scientific community in the initial selection of missions for study and will constrain the selection to match the available development funds. This new approach will allow missions completing their detailed design phase to transition smoothly into development without the long waiting period that has been typical for recent Explorer missions.

As a first step in this process, NASA released, in 1986, a Space Science and Applications Notice that invited proposals for Explorer concept studies. The invitation was also limited to the traditional Explorer scientific disciplines mentioned above. The goal of the concept study program is to identify a small group of particularly promising mission concepts that can be carried into feasibility studies for new Explorer missions. The concept studies will be funded at a level of about $400,000 each.

Forty-five proposals were received. Of these, nineteen were for astronomy and relativity missions, nine for high energy astrophysics missions, five for solar and heliospheric physics missions, eight for space plasma physics missions, and four for thermospheric and mesospheric physics missions. After a delay in the program, following the Challenger accident, NASA undertook a peer review of the proposals.

Four of the proposals have been selected for feasibility studies. These are:

The Advanced Composition Explorer (ACE):
A Scout-class mission designed to mount a coordinated attack on elemental and isotopic cosmic ray composition with a combination of five high-resolution spectrometers, each having a collecting power 1 to 3 orders of magnitude greater than previous or planned experiments;

The Far Ultraviolet Spectroscopic Explorer (FUSE or "Lyman"):
A Delta-class mission that employs an 80 cm diameter, grazing incidence telescope to study the structure and energy balance of the interstellar medium, and the physics of accretion disks, active galactic nuclei, and winds and coronae of both hot and cool stars, by observing spectra in the 910 - 1200Å band;

The Nuclear Astrophysics Explorer (NAE):
A Delta-class (Explorer Platform) mission which will use nine cooled germanium detectors to make high resolution ($E/\Delta E \sim 1000$) observations of gamma-ray lines at a sensitivity that is 100 times better than previous instruments in order to study nucleosynthesis, supernova dynamics, and neutron stars and black holes; and

The Mesosphere and Lower Thermosphere Explorer (MELTER):
A Scout -class mission carrying a payload of nine instruments designed to explore the chemistry, energy balance, global temperature structure, and transport of major and minor atmospheric constituents and their distribution in the mesosphere and thermosphere.

Each selected investigator will work with NASA to develop an understanding of all aspects of the mission: the scientific objectives, instruments, spacecraft, operations, data analysis, and costs. Each study will be led by a Principal Investigator who will manage the activity and document the outcome of the study, and each study team will work with technical teams from the NASA Goddard Space Flight Center to better develop the associated technical and programmatic information that will enable NASA to arrive at a decision in FY 1989 on the follow-on mission.

Following the completion of the feasibility studies, which started in April 1988, NASA, in consultation with scientific advisory committees, will evaluate the scientific merit, feasibility, and cost of each mission and its potential contribution to NASA's programs, and will select the missions which will continue into the definition study phase. NASA will also issue an AO for scientific participation in the definition studies. Following the successful completion of these studies, NASA will proceed directly into mission development without further competition. In this manner, NASA will shorten the delays from concept to development and flight but will still retain the competitive selection process.

The Explorer Platform

The Explorer platform is a reusable spacecraft which is based on the multimission modular spacecraft (MMS) and an equipment deck. The platform can provide spacecraft support for low Earth-orbit missions that require solar, stellar, or Earth pointing. The MMS, which has been used previously for both solar- and Earth-pointing missions, provides all utilities for the payload and can be serviced on-orbit. The platform can be launched by either a Delta-class ELV or the Space Shuttle. When launched from a Delta-class ELV, the platform can carry a 4000 lb payload and, when launched from the Space Shuttle, it can carry more than 10,000 lbs. The Explorer platform is designed to have a 10-year operational lifetime, assuming on-orbit servicing and an occasional reboost.

The Extreme Ultraviolet Explorer (EUVE) will be the first spacecraft to use the Explorer platform. Figure 1 is a line drawing of the Explorer platform with the EUVE payload. EUVE will be launched by a Delta rocket in 1991 and will operate for two years in space. In 1993,

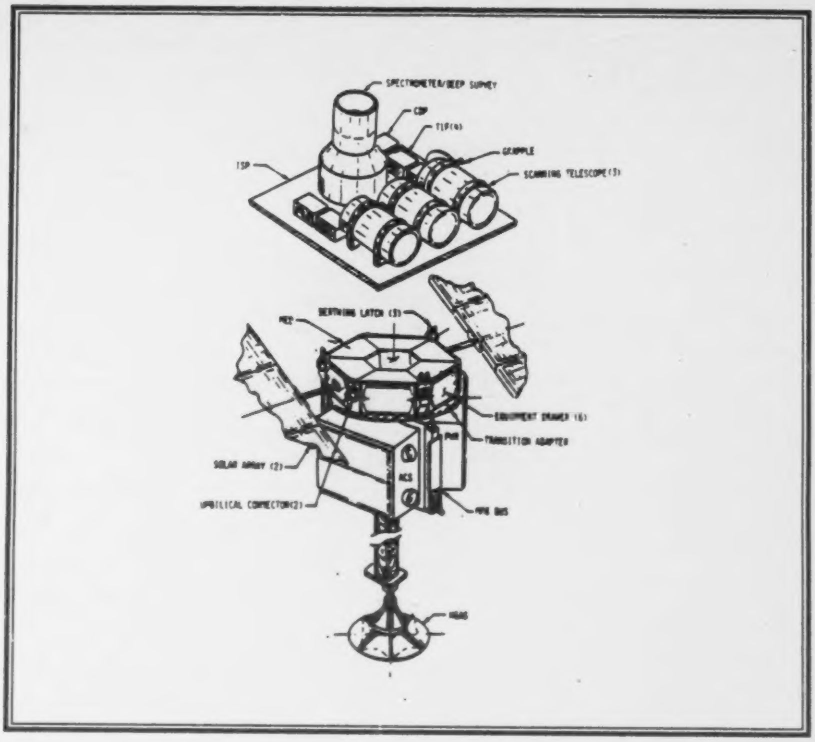
SPECTROMETER/DEEP SURVEY
CDP
TIP(4)
GRAPPLE
ISP
SCANNING TELESCOPE(3)
BERTHING LATCH (3)
MEP
EQUIPMENT DRAWER (6)
PWR
TRANSITION ADAPTER
SOLAR ARRAY (2)
ACS
UMBILICAL CONNECTOR(2)
MMS BUS
HGAS

Figure 1

The Explorer Platform, showing the Multimission Modular Support spacecraft, the equipment platform, and the Extreme Ultraviolet Explorer payload module. Note the three telescopes mounted perpendicular to the spacecraft axis and the one telescope mounted along the axis. The three telescopes will scan the sky while the single telescope points at objects co-aligned with the spacecraft axis.

the Space Shuttle will carry the X-ray Timing Explorer (XTE) payload and servicing equipment up to the Explorer platform. The EUVE payload and spacecraft will be brought as a unit into the Shuttle cargo bay where the EUVE payload will be separated from the Explorer platform. The XTE payload will then be attached to the platform and, after suitable checkout, the spacecraft and its new payload will be reboosted to its operational orbit. XTE will then operate in space for a nominal two year mission lifetime. Other missions, for example, the NAE, will be identified to follow XTE, such that the entire 10-year useful life of the Explorer platform can be fully used.

Missions of Opportunity

The fourth Explorer initiative is designed to enable the U.S. scientific community to capitalize, more productively, on flight opportunities offered on foreign space missions and on the space missions of other U.S. government agencies. The generosity of the U.S. in aiding and encouraging the development of foreign civilian space programs has, in addition to its immediate national benefit, begun to bring returns to U.S. investigators. Nations that have been assisted by the U.S. have now opened their missions to U.S. scientists. These missions of opportunity present one of the most promising avenues for U.S. scientists to obtain hardware flight opportunities, observing opportunities, and data access that are otherwise not available within the NASA flight program. The flexibility offered by the Explorer program is ideal for capitalizing on these opportunities.

Examples of such cooperations already exist in the Explorer program. As indicated previously, the German ROSAT mission will carry a U.S.- provided high resolution X-ray detector, similar to that flown on the HEAO-2 spacecraft in 1978. The U.S. will launch ROSAT with a Delta launch vehicle in 1990. In return, U.S. scientists will receive 50% of the observing time available during the pointing phase of the mission. The ROSAT sensitivity and X-ray collecting area are slightly better than the HEAO-2 spacecraft, but its energy range is lower than HEAO. The ROSAT mission helps provide a flow of data to the U.S. astronomical community, which received its last X- ray astronomy data from HEAO-2 in 1981.

Another mission of opportunity currently under development is the Solar-A mission. This is a cooperative mission between NASA and the Japanese Institute for Space and Aeronautical Sciences (ISAS). In this program, a U.S.-developed Soft X-ray Telescope (SXT) will be flown on the Japanese-developed Solar-A spacecraft, which is scheduled for launch by the Japanese in 1991. The scientific objective of this mission is to study high energy solar flares during the next period of peak solar activity. Also being planned is a U.S./Japanese collaboration on the Japanese high sensitivity X-ray observatory Astro-D. In this case, the U.S. and Japan will collaborate in the development of conical foil X-ray telescopes and CCD camera. Japan will provide the Astro-D spacecraft and will launch and operate the spacecraft. Observations and data analysis will be shared.

Finally, a Combined Release and Radiation Effects Satellite (CRRES) is being developed jointly between NASA and the Department of Defense. In this interagency cooperative mission of opportunity, designed to study the complexities of the Earth space environment by a synergistic combination of active probing and passive observations, NASA is providing twenty-four chemical release canisters which will be released into the ionosphere from the CRRES. The U.S. Air Force Space Test Program will provide the spacecraft and remaining payload. CRRES will be launched by an Atlas Centaur in June 1990.

Additional missions of opportunity may appear as other countries continue to plan their space programs with consideration for cooperative involvement of NASA. The Scout-class Explorer initiative is structured to enable foreign space agencies to participate in that aspect of the program. The Explorer program will assure a continued ability to respond rapidly to such opportunties by allocating 15% of its budget to the support of missions of opportunity.

CONCLUSIONS

The Explorer program has provided U.S. scientists in widely ranging scientific disciplines with an unprecedented opportunity for exploration, discovery, and fundamental research during the past thirty years. The mission success rate has been high and the scientific return large. The program has provided significant benefits in the education of U.S. scientists, engineers, and program managers and in foreign policy. Until the mid-1970's, Explorers were spacecraft which provided an intermediate research capability between sounding rocket flights and orbiting observatories. They were reasonably inexpensive, could be developed quickly, and provided frequent opportunities for space experiments. During the past decade, however, Explorers have become increasingly complex, expensive, and infrequent.

Arguments have been presented by the National Academy of Sciences in their reports "The Explorer Program for Astronomy and Astrophysics" and "A Strategy for the Explorer Program for Solar and Space Physics" to increase the Explorer budget. The reports present arguments that an Explorer program budget of $130 million (1988 dollars) per year will make it possible for NASA to reach an Explorer launch rate of approximately one mission per year of combined Scout class and Delta class spacecraft. The reports state that such a long-term commitment to a launch rate of one mission per year will recapture the strength and scientific vitality of the early Explorer program. NASA is evaluating these recommendations and, in parallel, is proceeding with the Explorer Platform, the Explorer concept studies, and the missions of opportunity to increase the frequency of Explorer opportunities. The Scout Explorer initiative is awaiting Congressional action on the President's FY 1989 budget.

The initiatives being planned and those already undertaken by NASA in the Explorer program are reopening avenues for broad participation by the U.S. research community in the development of space flight hardware, the operation of space instrumentation, and the analysis of fresh scientific data from space. With the help of the Congress, the NASA Explorer initiatives will provide a new enthusiasm for space research and a new opportunity for the U.S. academic community to regain its lost scientific momentum.

APPENDIX

THE HISTORY OF THE EXPLORER PROGRAM

The Explorer program began with the launch of Explorer I as the U.S. entered space in February 1958. Scientists, who were active cosmic ray and upper atmosphere researchers, and astronomers, who recognized the benefits to be gained by placing instruments above the atmosphere, were quick to grasp the opportunities provided by space technology. A strong scientific interest in using Explorer spacecraft also developed rapidly among atmospheric scientists and ionospheric physicists, who saw for the first time the opportunity to directly measure the constituents of upper atmosphere and the ionosphere above the reflecting E and F regions. The Explorer spacecraft rapidly became the workhorse of these disciplines.

Space Physics

Explorers 1 and 3 carried Geiger counters into orbits above the Earth. The instruments registered unusually high counting rates, and it was at first believed that the instruments had malfunctioned. James Van Allen of the University of Iowa correctly interpreted these rates, however, as evidence for the presence of powerful belts of radiation trapped around the Earth. The Norwegian physicist, Carl Stoermer, had predicted, in about 1900, the trapping of charged particles in the Earth's magnetic field and had calculated orbits for such particles.

Nicholas Christofilos, of the Lawrence Radiation Laboratory, also predicted that the nuclear fission products from high altitude nuclear weapon tests would become trapped in the Earth's magnetic field and would form artificial belts of radiation around the Earth. Explorer 4, which was designed to test this theory, was authorized on May 1, 1958, and was launched on July 26, of the same year. The spacecraft detected the radiation from the Argus nuclear weapon tests detonated over the south Atlantic, as well as the natural radiation environment. The evidence, from a controlled experiment, that the Earth could trap and retain energetic charged particles, gave tremendous impetus to further study of the phenemena.

Van Allen and his colleagues established that, in addition to the belts of artificial radiation, the Earth had two separable belts of radiation. Carl McIlwain, also of the University of Iowa, developed a system of magnetic coordinates, based on the Earth's magnetic field and the Earth's radius, that was particularly effective in organizing the trapped radiation data and could explain, in a quantative manner, that the radiation was trapped into belts around the Earth. Explorers 6 and 7 were designed to study further the Earth's radiation belts. Explorer 6 carried meteorological instruments. The Explorer 6 camera returned the first picture of the Earth taken from space.

In 1931, Sidney Chapman and V.C.A. Ferraro predicted that the Earth's magnetic field would be confined during a magnetic storm to an elongated bubble around the Earth. Explorers 10, 12, 14, and 15 were all equipped with magnetometers, plasma probes, and energetic charged particle detectors. These instruments provided further detail of the Earth's radiation belts and Explorer 12 observed the sudden dropping to zero of the radiation belts. The apparent boundary to the radiation belts was termed the magnetopause, and the region inside the boundary was termed the magnetosphere. Both terms relate to the confinement of the phenomena of the Earth's magnetic field by the charged particle plasma from the Sun, the solar wind.

Explorer 18, which was the first of the Interplanetary Monitoring Platform (IMP) series of spacecraft, verified that the magnetosphere was separated from the solar wind by a standing shock wave in the solar direction. The IMP series has been one of the most scientifically productive series of spacecraft ever launched. Beginning with Explorer 18, the IMP's systematically mapped out the Earth's radiation environment, the near-Earth solar wind, and the details of the magnetospheric collisionless shock wave. IMP spacecraft have been placed in deep interplanetary Earth orbits and IMP-E (Explorer 35) was put into orbit around the moon, thereby providing detailed observations of the particles and fields environment around the moon. The IMP's also explored the region in the tail of the Earth's magnetosphere to better understand the flow of plasma and magnetic fields around and away from the Earth. The IMP series of Explorers consisted of 10 spacecraft, all of them exceptional scientific successes.

By the early 1970's, the direct space plasma environment of the Earth and the characteristics of the solar wind were, in general terms, well known. The very basic question of the mechanism to transfer energy from the solar radiation down through the radiation belts and Earth's magnetic field into the upper atmosphere and ionosphere was, however, still unanswered. This led to the next group of Explorers, the International Sun-Earth Explorers (ISEE), the Dynamics Explorers (DE), and the Atmospheric Explorers (AE).

The International Sun Earth Explorers (ISEE) were a group of three spacecraft designed to investigate, in a coordinated manner, the energy input from the solar wind into the outer and intermediate magnetosphere and the resulting changes deeper in the magnetosphere. The ISEE series was carried out in cooperation with the European Space Agency (ESA). The Dynamics Explorer (DE) mission, which consisted of two spacecraft, was launched in 1981. The objective of the DE was to better understand the direct energy coupling between the Earth's immediate space environment and the energy output from the Sun. The two DE spacecraft were launched into co-planar polar orbits, one with an apogee of 24,775 km and the other with an apogee of 999 km, thereby enabling complementary data to be obtained at different altitudes.

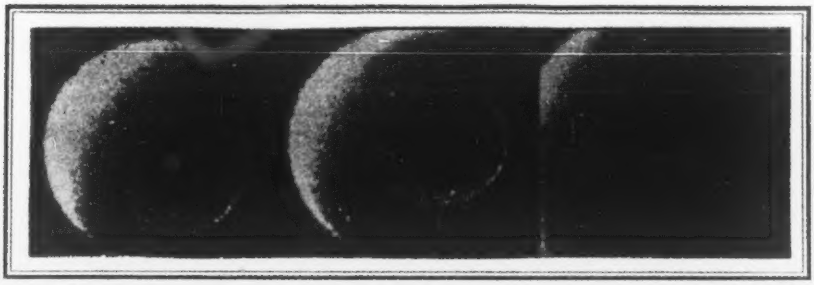

Figure A-1

Three views of aurora from the Dynamics Explorer (DE-1)

The DE investigated the interactive coupling processes between the Earth's magnetosphere and ionosphere and atmosphere. Three views of the aurora, taken from the DE-1 spacecraft, are shown in Figure A-1. The ISEE spacecraft provided data on the solar input to the magnetosphere and the transport through the outer magnetospheric bow shock and magnetopause and the Atmosphere Explorers (AE), launched October and November 1975, provided data on the effect of solar radiation on the ionosphere and upper atmosphere. This well-conceived team of spacecraft was able to mount a coordinated scientific attack on Sun-Earth coupling that would not have been possible had it not been for the programmatic flexibility embodied in the Explorer program. The ISEE and DE spacecraft, together with the IMP's, are largely responsible for the data that led to the current understanding of the solar-terrestrial environment.

ISEE-3 was an exceedingly versatile mission. It was designed to remain in deep space, outside the magnetosphere, to measure the solar input to the Earth's magnetosphere. At the time of its launch in 1978, no thought had been given to other objectives. Scientists at the NASA Goddard Space Flight Center, however, realized that by redirecting the spacecraft into a near lunar flyby, the spacecraft could be accelerated onto a trajectory to encounter the comet, Giacobini-Zinner. After the fifth lunar flyby, on December 22, 1983, ISEE-3 was accelerated out of the Earth-Moon system on a trajectory toward Giacobini-Zinner. During its final lunar flyby, ISEE-3 passed within 120 km of the lunar surface. At this time, it was renamed the International Cometary Explorer (ICE). On September 11, 1985, ICE passed through the tail of Giacobini-Zinner and measured the particles, waves, and fields in the comet's tail. The amazing feat of the ICE/ISEE-3 spacecraft was that it was not designed for a cometary encounter, but rather, was a relatively low-cost interplanetary particles and fields spacecraft. It was through the ingenuity, imagination, and cooperation of the ISEE principal investigators, the spacecraft controllers, and the mission managers, that this feat could be accomplished.

Recently a new Space Physics Explorer was successfully launched. San Marco D, in the continuation of a long-standing cooperative program with Italy, carries five instruments to study the lower atmosphere. The three scientific instruments that measure neutral wind and particle temperature, electric fields, and the velocity of ions in the lower atmosphere, are provided by investigators from the U.S. The Italian instruments will measure the density of the neutral atmosphere, and an instrument from the Federal Republic of Germany will measure equatorial airglow, solar extreme ultraviolet radiation, and radiation from the sun, the Earth's surface, and from clouds.

The spacecraft was launched with a Scout rocket from the San Marco platform, off the coast of Kenya in March 1988. San Marco D is the fifth in the San Marco cooperative series, all of which were launched from Kenya. The first San Marco was launched in 1964 and was followed by launches in 1967, 1971, and 1974. The San Marco launches are unique in that the U.S. Scout launch vehicles are processed and launched by an Italian crew. To date, there have been eight Scout launches from the San Marco platform, *all of them successful.*

Space Astronomy

Since the beginning of ground-based astronomy, astronomical observations have been restricted to the narrow visible and radio portions of the electromagnetic spectrum. In the 1950's, astronomers also recognized that spacecraft carrying instruments above the atmosphere would make possible measurement at the wavelengths absorbed by the Earth's atmosphere. Observing in these previously inaccessible energy bands held the potential of revealing entirely new phenomena and physical processes that were unknown on Earth because they originate in extreme conditions of temperature, pressure, gravity, and magnetic fields in astronomical objects. For example, in a pioneering paper in 1958, Phillip Morrison of the Massachusetts Institute of Technology predicted that celestial objects would emit observable quantities of gamma rays from very high energy physical processes ocurring in these objects.

Showing again the ability to respond to new scientific ideas, the Explorer program in 1961 opened the field of space astronomy with the launch of Explorer 11. This mission carried a directional detector designed to search for high energy gamma rays from the interactions of cosmic-ray nuclei with interstellar matter. Thirty events with possible gamma-ray signatures were recorded from space. Their rate of occurrence implied an upper limit on the intensity of cosmic gamma rays. The observations also disproved one version of the steady-state theory of cosmology whereby matter-antimatter pairs were assumed to be continuously created everywhere so as to maintain a constant density in the expanding universe. Explorer 11 proved the presence of gamma rays in space and established the new field of gamma-ray astronomy. Explorer 11 clearly demonstrated the astronomical importance of space observation platforms.

In 1960, sounding rocket observations found an object in the constellation Scorpius that was emitting copious amounts of X-rays. Instruments flown of subsequent sounding rockets provided identifications of 30 astronomical X-ray sources. These rocket discoveries, and the results from Explorer 11, led NASA to begin a series of astronomical Explorers, called the Small Astronomy Satellites (SAS), which were dedicated to pursuing the recent discoveries in X-ray and gamma ray astronomy. The first and third missions of the SAS series were devoted to X-ray astronomy and the second to gamma ray astronomy.

SAS-1 (Explorer 42) was also called Uhuru because it was launched in Kenya on Kenyan independence day. SAS-1 provided the first comprehensive sky survey in X-rays. It discovered several hundred galactic and extragalactic X-ray sources (Figure A- 2) and it provided the observational foundation for the development of observational X-ray astronomy. SAS-1 was able to measure the position locations of many X-ray sources with sufficient accuracy to enable identification of their optical counterparts. SAS-1 also discovered pulsating X-ray stars in binary systems that are rotating, accreting, magnetized neutron stars, and SAS-1 observations measured the unique temporal variations in Cygnus X-1 that support the idea that Cygnus X-1 is a black hole in a close binary system. Extragalactic sources revealed variable X-ray emission from active galactic nuclei. Hot intergalactic plasma was found in certain clusters of galaxies with a total mass comparable to the total visible mass of the galaxies in the cluster.

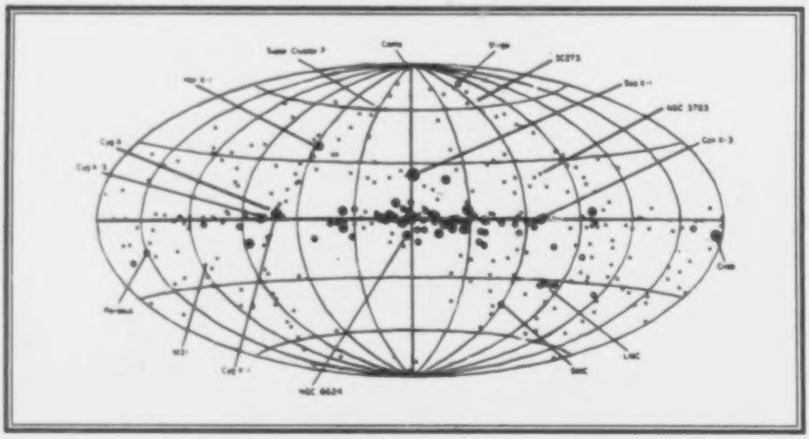

Figure A-2

X-ray sources from the SAS-1 (Uhuru) source catalog, showing the 339 observed sources. The size of the source symbol is proportional to the logarithm of the peak source intensity.

The second Small Astronomical Satellite (Explorer 48), carrying a high energy gamma-ray telescope, confirmed the discovery of galactic and extragalactic gamma rays by Explorer 11 and the Orbiting Solar Observatory 3 (OSO-3). One of the attractive features of gamma ray photons, in addition to their ability to carry information on high energy physical processes, is that much of the universe is transparent to gamma rays. Gamma ray astronomy is, therefore, an excellent tool to map regions of space that are obscured at other wavelengths. SAS-2, during its lifetime, mapped the intensity of high-energy gamma rays over about 60 percent of the sky, including most of the galactic plane. The distribution of gamma-ray emission appeared generally correlated with galactic structural features, including spiral arm segments, as expected from cosmic ray interactions with the interstellar gas. The uniformity of the measurements of diffuse gamma radiation clearly eliminated the galactic halo as the primary source. The intensity, uniformity, and energy spectra, when combined, seem to limit the possible origins to two: active galaxies or matter-antimatter interactions at the boundaries of superclusters of galaxies. This question remains open and will not be answered until the Gamma Ray Observatory is launched in 1990. Observations of some point sources, identified by SAS-2, showed pulsations or variability. In addition, strong gamma ray sources were discovered that could be associated with optical counterparts.

SAS-3 was an X-ray astronomy spacecraft which spanned the energy range from 0.1 to 50 keV. Among its results were the discovery and analysis of rapid X-ray bursters and many new X-ray burst sources. The SAS-3 observations led to the conclusion that a burster is a weakly magnetized neutron star accreting matter from a low mass companion, and to the identification of two types of X-ray bursts of which one is caused by fluctuations in the accretion flow and the other by thermonuclear flashes in material accumulated on the neutron star surface.

Timing studies of binary X-ray pulsars, including several discovered with SAS-3, yielded numerous precise orbit determinations and strong evidence that the masses of the neutron stars in such systems all lie within a narrow range. Position determinations of over 60 galactic and extragalactic X-ray sources led to more than 40 new optical identifications including a nearby quasar, and the first counterpart of an X-ray burster.

An Explorer guest investigator program was begun with SAS-3. This program allowed other scientists to perform observations with the satellite. The guest observer program signaled the beginning of a rewarding new phase in space research with Explorers.

Radio Astronomy Explorer 1 (RAE-1), the first spacecraft designed specifically for radio astronomical studies, provided measurements over the frequency range 200 kHz to 9.2 MHz. Although the most extensive results from this mission were directed towards solar system astronomy and space plasma physics, observations were also made of galactic sources. Continuum background maps at frequencies of 4 and 6 MHz defined the distribution of the ionized component of the interstellar medium. Cosmic noise background, measured down to 0.5 MHz, provided new estimates of the interstellar flux of cosmic rays, of magnetic fields in the galactic halo, and of the nature of radiation from distant extragalactic radio sources.

The second spacecraft dedicated to observations at radio frequencies, the RAE-2, was put into a lunar orbit in order to reduce noise contamination from terrestrial radio emissions. Its orbit resulted in repeated lunar occultations of the Earth, providing shielding from the Earth and enabling galactic measurements to be made without interference. New measurements of the nonthermal galactic radio spectrum, at frequencies below 10 MHz, survey maps of the spatial distribution of the low frequency galactic emission, and unique measurements of the source locations of the Earth's auroral kilometric radiation were obtained. The lowest frequencies allowed construction of a coarse picture of the local interstellar medium and its magnetic field in the immediate solar neighborhood.

Occasionally, a scientific investigation that begins with a rather modest goal exceeds all expectations of scientific return and becomes world reknown for its greatness. Such was the case with the International Ultraviolet Explorer (IUE). IUE was developed to measure ultraviolet spectra of astronomical objects. It consists of a small (0.45m diameter) ultraviolet telescope and spectrographs and camera. IUE was placed in geosynchronous orbit in 1978. It is a cooperative mission between NASA, the European Space A~~gency (ESA),~~ and the Science and Engineering Research Council (SERC) of the United Kingdom. The observing time and spacecraft control are shared by the sponsoring agencies. After ten years of continuous operations on-orbit, IUE is still producing valuable scientific results and has become one of the most productive scientific instruments ever created.

Spectra from IUE have revealed a hot halo surrounding our galaxy and variability ascribed to different regions within active galactic nuclei. Observations of the stars have demonstrated that winds and mass loss exist in practically every kind of star and have led to the discovery of accretion disk phenomena connected with compact objects. A comprehensive picture of magnetic activity, evidenced by chromospheres, coronae, and extended atmospheres, has been developed for large numbers of cool stars. Studies of comets have revealed new molecules. Spectral observations of Comet Halley complemented the imaging from an international fleet of spacecraft and confirmed the source of ultraviolet emissions discovered by Pioneer Venus. Planetary aurorae, associated with Jupiter, Saturn, and Uranus, have also been monitored.

Infrared astronomy had a beginning similar to X-ray astronomy. The physically most interesting portions of the infrared spectrum are absorbed by the atmosphere and cannot reach the surface of the Earth. Observations from balloons and very high altitude aircraft showed the richness of the infrared sky, but the observational altitude, stability, and length of time available for observations were inadequate to perform the thorough survey that was required to establish the field as a fruitful area of scientific research. NASA recognized the need for a more sophisticated mission, and, in the 1970's, began discussions with The Netherlands to develop an infrared Explorer. The outcome of these discussions was an agreement to proceed with the Infrared Astronomical Satellite (IRAS). At that time, the United Kingdom also joined the collaboration.

The IRAS mission, launched in 1983 into polar sun-synchronous orbit, carried a 60 cm telescope, cooled to operating temperatures by liquid helium. Because of the limited supply of helium, IRAS had a lifetime of slightly less than 1 year. Nonetheless, its scientific impact was as much or more than had been expected.

IRAS made a survey of the entire sky at wavelengths of 12, 25, 60, and 100 μm. The primary products of the mission were a catalog of 245,000 point sources (stars, galaxies, and star formation regions) and a set of 212 images, covering the entire sky with 2 arc minute resolution in the four wavelength bands. Figure A-3 is a copy of the IRAS sky map showing the distribution of infrared radiation along the plane of our galaxy.

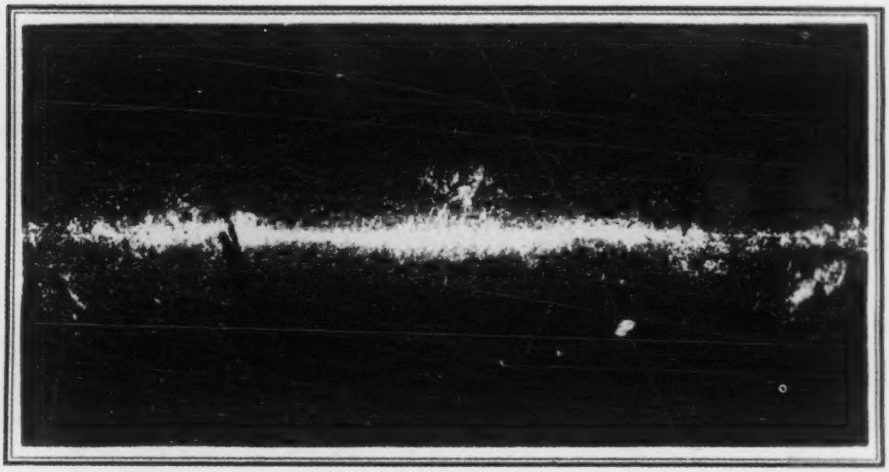

Figure A-3

The IRAS sky survey map showing the striking features of the solar system, the extrasolar point and diffuse infrared sources.

Studies of IRAS data show that a significant number of nearby dwarf stars have a far-infrared excess due to an extended disk or shell of solid material orbiting around and heated by the central star. This solid material is believed left over from the star formation process and represents protoplanetary material. Very small amounts of warm interstellar dust have also been discovered that can be used to trace out the local interstellar matter, to investigate the dust-to-gas ratio, and to define extinction-free areas in the sky. Stars of one solar mass or less have been revealed in the process of formation in nearby molecular clouds, such as Taurus.

Some 20,000 spiral galaxies were detected by IRAS. Many of these galaxies emit 5 to 1,000 times more energy in the infrared than at visual wavelengths. Some of these are galaxies harboring recent episodes of star formation ("starburst" galaxies), others may emit copious amounts of infrared radiation due to the presence of dust-embedded active nuclei. IRAS has also contributed significantly to the study of comets, asteroids, and dust within the solar system.

The IRAS catalog has been widely distributed to astronomy research centers throughout the world. The IRAS data are archived in an IRAS data center at the California Institute of Technology, and, four years after the end of the IRAS mission, its data are still sought after for astronomical research, both among the original IRAS investigators and through an active guest observer program.

A total of eight dedicated astronomical Explorers have been launched by NASA. The accomplishments of these missions have enlarged our understanding of practically every branch of astronomy and astrophysics. The far reaching scientific significance of this modest group of Explorer missions will not be fully appreciated for decades.

Complementary Astronomical Observations

In addition to the Explorers that were devoted exclusively to astronomy and astrophysics, a number of astrophysics experiments have been carried out aboard Explorers that concentrated on other branches of space research. Cosmic ray investigations provided some of the earliest astrophysics results from the Explorer Program. A series of experiments carried aboard IMP's 1 through 8 (designated Explorers 18, 21, 28, 34, 41, 43, 47 and 50, respectively) made fundamental contributions to the study of cosmic ray spectra and composition. In the 1960's, instruments carried on Explorers demonstrated that the relative abundances of major elements are similar in galactic cosmic rays and in solar system matter. These demonstrations led to the conclusion that the relativistic charged particles that permeate the galaxy are formed by normal processes of stellar nucleosynthesis.

The most recent experiments have resolved the individual isotopes of some of the elements and have found significant excesses (relative to solar system matter) of neutron rich isotopes of the elements neon, magnesium, and silicon. These excesses indicate the possibility of there being regions of the galaxy with sizable metallicity enhancements or, alternatively, suggest a connection between cosmic ray injection and objects with peculiar surface abundances. Experiments aboard the IMP satellites discovered the low energy "anomalous component" of cosmic rays, now widely believed to be a population of particles accelerated from the local interstellar gas, and they demonstrated that this material does not contain the products of nuclear fragmentation that are characteristic of galactic cosmic rays. Explorer-borne experiments also measured the abundances of several long-lived radioactive isotopes, which were used as "clocks" to establish that cosmic rays are confined by the galactic magnetic field for approximately 10 million years.

Gamma-ray detectors were also carried on several satellites of the IMP series and made fundamental discoveries concerning the surprising gamma-ray bursts. Bursting gamma- ray sources were found in data from the Vela nuclear test detection satellites in 1967. IMP-6, with detectors sensitive to the 0.1-1 MeV energy range, provided the first verification of the gamma-ray burst phenomenon and obtained the first spectral measurements of gamma- ray bursts. Instruments on IMP-7 measured the spectra of about 25 gamma-ray bursts and demonstrated their similarity when averaged over the burst duration. ISEE-3 also carried instruments for the study of cosmic gamma-ray bursts. These instruments, used separately and in conjunction with experiments carried by an international network of spacecraft, made important contributions to the study of burst source spectra and locations. A list of all past and presently approved Explorers is shown in Table I.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

AUG 4 1988

Honorable Bill Nelson
Chairman
Subcommittee on Space Science
  and Applications
Committee on Science, Space
  and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

As a follow-up to our discussions during the hearings last Spring, I am sending you a copy of the strategic plan on microgravity. This has been developed by the Office of Space Science and Applications in cooperation with the other program offices involved to explicitly outline the frame work for development of a more specific research plan. That plan will be developed over the next several months. I will keep you informed of our progress in this area.

I appreciate your interest and support of our program in this important area.

Sincerely,

Dale D. Myers

Dale D. Myers
Deputy Administrator

Enclosure

cc: Honorable Robert S. Walker

NASA Microgravity Strategic Plan

This report has been prepared for use as an internal NASA document and will serve as the basis for NASA program planning in the future.

August 3, 1988

NASA MICROGRAVITY STRATEGIC PLAN

PREFACE

As part of its mandate to guide the United States' civil space program, the National Aeronautics and Space Administration (NASA) is committed to preserving U.S. preeminence in critical aspects of space science, applications, and technology. NASA's goals also include obtaining scientific, technological, and economic benefits through space-related activities, encouraging U.S. private sector investment in space, and improving the quality of life on Earth.

The space environment offers unique opportunities for research and development in the fundamental sciences, materials science, and the life sciences. The on-orbit microgravity environment with reduced buoyancy forces, hydrostatic pressure, and sedimentation, is a particularly promising area to explore. Long exposure to a virtually zero-gravity environment is a unique situation that cannot be duplicated or even approximated for any length of time on Earth. In addition, the near-Earth orbit offers a unique contamination-free vacuum capability.

Of the research to be done in this environment, basic research would include the behavior of fluids and the study of transport phenomena in microgravity, as well as experiments that make use of the enhanced precision possible in microgravity to measure physical properties and to validate contemporary theories of relativity and condensed matter physics. Applied microgravity research both by NASA and its industrial partners could provide fundamental insights that would lead to better control strategies for Earth-based processes and also lead to the production of new benchmark materials with unique properties that cannot be produced on Earth.

Pioneering efforts such as these will challenge and motivate this Nation to new standards of excellence, and it will stimulate exciting developments in science, technology and space commercialization that will be crucial to our economic growth and success in the 21st century. Successful exploration and development of the near-Earth space environment and the microgravity effects, requires a vision of the future, defined goals consistent with the national interest, and well conceived strategic, development, and operational plans.

This document is NASA's agency-wide microgravity strategic plan, which addresses research, applications, and commercialization for the 1990's. The plan presents an analysis of the current situation, identifies critical factors, and defines goals, objectives and strategies, which are intended to:

- provide a context for decision making, assure realism in long-range planning, direction for hardware development and
- establish a framework for developing a National Microgravity Research Plan.

VISION OF THE FUTURE

Early in the 21st century, a permanently manned, on-orbit microgravity research, development, and pilot production facility is envisioned to be operated in many respects like a National Laboratory. The Space Station will be the centerpiece of this capability, however, private sector and foreign-developed carriers and platforms may be included. It may also incorporate space vacuum facilities for contamination free processing.

In the 1990's, NASA in conjunction with U.S. industry, other federal agencies, and international partners will have qualified, developed, and begun to exploit the capabilities of the Space Station and other on-orbit facilities. The key elements of NASA's vision, "to develop near-Earth space as a national resource," are:

- A multidisciplinary program of fundamental microgravity science in space that contributes to the peaceful, international use of space.
- A flow of practical benefits through utilization of a multicapability infrastructure in space for microgravity research.
- Emergence of a viable, competitive U.S. microgravity-based industry capable of aggressive commercial application of microgravity research advancements.
- Strengthened U.S. competitiveness in international commerce through preeminence in materials science and processing technologies.

CURRENT STATUS

NASA's Office of Space Science and Applications (OSSA) conducts a program of enabling research in the space environment to explore the effects of microgravity on basic physical, chemical, and biological processes. In addition, OSSA pursues applied research on processing biomaterials; electronic and photonic materials; metals, alloys and composites; glass and ceramics; and polymers. These NASA-funded, non-proprietary investigations are conducted by university, industry, and government researchers using both ground-based facilities and flight experimentation.

NASA's Office of Commercial Programs (OCP) sponsors industrial research and program initiatives that encourage the participation, funding of research, and commercial commitment of U.S. industry to space endeavors. Because many microgravity applications show commercial potential, it is imperative that a close partnership between government and industry be formed, analogous to that successfully demonstrated in NASA aeronautical research.

Joint government and industry programs are underway in Europe, Japan, and the Soviet Union. These programs are carefully planned and well funded. The U.S. can derive considerable value from international cooperation, particularly in basic microgravity research and hardware development. However, extending proprietary protection and a competitive edge to U.S. industry for applied research is an associated challenge that NASA accepts.

The 1986 Challenger disaster has significantly delayed NASA and the free world's flight program and the lack of timely and predictable access to space has caused considerable concern and eroded confidence among academic, industry, and international participants. However, during this time the recommendations of several well-qualified NASA advisory bodies have been implemented. These include plans for a microgravity dedicated series of Spacelab flights (USML), a new generation of multiuser facility-class hardware, an extended duration orbiter and private sector developed carriers.

During the last two years, NASA's microgravity science and applications programs have matured significantly and are more realistic in scope and objectives. There is cooperation and coordination between OCP and OSSA reflecting their interdependence and a considerable potential for synergy. Congress, the Administration, and NASA continue to support and endorse an expanded microgravity research and development effort.

The goals and objectives of this NASA Microgravity Strategic Plan, are based on certain pivotal considerations:

1) The need for manned presence.

Materials science and process research are experimental endeavors involving some empiricism and it is essential, in most cases, to have a manned-presence to conduct interactive and iterative experiments. Only through this process of learning by doing can new materials and processing techniques be developed that take full advantage of the microgravity environment. Also, the experience of living and working in the microgravity environment will suggest new concepts for processing of materials that are not possible on Earth. The ability to explore and develop these concepts will evolve new processing techniques that may result in materials with unique and possibly superior properties.

Appropriate use will be made of automation, telescience operations, and expert systems particularly where processes are well defined. Many operations such as repair, refurbishment, or reconfiguring of experiment or production modules can be best performed through servicing on orbit by Space Shuttle or Space Station based astronauts.

2) The need for state-of-the-art hardware.

Flight experience with the current hardware inventory has shown that a front-end investment in technology and equipment specific to microgravity research is essential. OSSA is currently involved in an extensive program of experiment hardware and facilities development to provide research capability necessary for scheduled USML flights and eventually the Space Station. The Space Shuttle, Spacelab, a Commercially Developed Space Facility (CDSF) and the manned Space Station will constitute an integrated carrier sequence that permits an evolutionary approach to microgravity research and hardware development. Experiment facilities can be developed on the ground, tested and refined aboard short-duration Spacelab flights and then deployed for longer duration on the Space Station for further manned experiments or a CDSF if the process can be automated. This sequence ensures maximum scientific return from planned investigations, encourages the growth of a vigorous microgravity research community and increases the early opportunity to identify and refine new techniques and processes of commercial value to ground-based U.S. industry.

The early availability of Spacehab or a CDSF used in the attached mode will accelerate both the science program and hardware development; however, only the Space Station can provide the necessary manned presence, power, and versatility required to explore and develop many of the most promising microgravity applications. Once Space Station is in operation the CDSF would continue to be utilized in the free-flyer mode, providing a long duration microgravity environment for automated processes.

A free-flying, space vacuum facility is also contemplated. By virtue of its orbital velocity, such a facility can produce a contamination free vacuum behind a special shield. The ultra-low vacuum with near infinite pumping speed, and ability to rapidly reject heat enable numerous processing techniques and also complement the associated microgravity capabilities.

The eventual development of a free-flying nano-g facility, which can compensate for residual atmospheric drag is envisioned. This facility would make it possible to conduct sophisticated experiments bearing on fundamental theories of condensed matter physics and relativity.

3) The need for cooperation and partnership.

Various nations are now positioning to compete in materials and process research in space. To maintain scientific leadership it is imperative that NASA conduct an aggressive, high-quality microgravity research program and foster productive partnerships among the industry, academic, and government research communities. Research results demonstrating the benefits and limitations of the microgravity environment must be promptly and effectively reported. Increased and timely access to space, prompt and responsive review procedures, and reduced costs and time required for developing, integrating, and operating experiments in space must be provided to researchers. One measure of NASA's success in developing the space frontier will be the degree to which industry and other government agencies participate and invest in space research, development, and commercialization efforts.

GOALS OF THE NASA MICROGRAVITY PROGRAM

1. Conduct a comprehensive research program in materials science, biotechnology, and fundamental physics, chemistry and biology through investigations in space.

2. Expand and facilitate an interdisciplinary research community, united by shared goals and resources, to conduct research in the space environment.

3. Establish a permanently manned, multi-facility national microgravity laboratory in low-Earth orbit to provide a long duration, stable microgravity environment. In addition to its other functions, the Space Station would also be the centerpiece of this capability.

4. Develop and demonstrate new technologies, materials, and processes relevant to basic research and commercial applications through utilization of the space environment.

5. Transfer to industry the technology and "know-how" supporting new, commercially-viable products, services and markets resulting from microgravity research.

6. Support, on a reimbursable basis, the launch and operation of private sector facilities and experiments. Continue to encourage the launch of microgravity research payloads by the private sector.

PRIORITIES AND DECISION MAKING PROCESS

In order to take full advantage of microgravity research, it is essential to have a permanent laboratory in space with sufficient resources to allow scientists to experiment on a routine basis as they are able to do in their terrestrial laboratories. The U.S. Laboratory Module on the Space Station is being designed and equipped for this purpose and will serve as the centerpiece of a national microgravity laboratory which would be operated very much like any other National Laboratory. In such a laboratory it will be possible to carry out the reproducible and iterative experiments required to perfect a process without having to wait a year or more for the next flight opportunity to make an adjustment in the processing parameters.

To prepare for Space Station and to be ready to make effective use of its capabilities starting in the 1995 timeframe, a number of important steps must be taken in the next few years. Experiment facilities must be defined and developed. New technologies needed to assure that the facilities will remain state-of-the-art into the 21st century must be identified and pursued. Experiment modules that will be elements of the experiment facilities of the Space Station must be developed and tested on Shuttle flights using Spacelab, Spacehab, or a CDSF. The users community must be strengthened. Finally, and most important, **a solid scientific rationale for use of microgravity must be established through high quality experiments that clearly delineate the advantages of the microgravity environment.**

To accomplish the objectives of the Flight Experiments Development Program funded under the Program Operating Plan (POP), the following tasks and decision rules have been established.

1. Develop high quality science experiments and modular multi-user apparatus for the USML/IML series of flights: This series of flights is crucial to the development of the Microgravity Science and Applications Division's (MSAD) program because it represents a continuity of microgravity-emphasis

flight opportunities that will allow the development and testing of experiment modules that will eventually become elements of the Space Station experiment facilities. Also, these flights will generate an early scientific return from high quality microgravity experiments performed in a well-characterized and controlled microgravity environment.

Factors to be considered in the determining the relative priorities of experiments to be conducted on USML missions are quality of science, pertinence to commercial interests, commitment to non-NASA supported experiments, and relative resource requirements.

2. Development of Principal Investigator (PI)-specific apparatus for carrying out high quality experiments which address fundamental physics and chemistry: Generally this apparatus is designed to carry out a specific experiment and is not suitable for multiple users, however, the potential scientific return would greatly elevate the program's status in the scientific community and would stimulate interest in other experiments of this nature. Also, several of these investigations can be expected to carry over into Space Station operation. Some of this apparatus may prove to be very expensive because of the high degree of sophistication required to challenge theories of contemporary science. The development of new or additional experiment apparatus will have to be phased into this level-of-effort program and may have to wait the completion of other projects unless the MSAD program receives additional funding. Generally, the priority within this category will be given to the projects that are nearest to being completed in order to reduce PI costs and to allow new projects to be started.

3. Definition studies for Space Station facilities: It is important to begin such studies at this time, but major expenditures for the development of such facilities cannot be intelligently made until we have better understanding of the Space Station interfaces and have gained experience with the experiment modules being developed for the USML series. A systems engineering effort has been started to identify common subsystems, standardize reliability and quality assurance procedures, and to work with the developers of the various Experiment Modules to insure optimum interface compatibility with Space Station. Priority for funding of this category will increase next year, as the Space Station Critical Design Review (CDR) is approached.

4. Development of science and apparatus for secondary payloads including Shuttle middeck and the Materials Science Lab (MSL) truss: The use of secondary flight opportunities can augment the number of flight opportunities available to the MSAD Program. However, there are a number of factors that make secondary flight opportunities less attractive; i.e.,

uncertainties in scheduling, unpredictable and perhaps unfavorable acceleration environment due to mission priorities, and generally fewer resources than can be provided on a dedicated mission. Nevertheless, effective use can be made of these opportunities if care is used in matching the experiment requirements to the mission capabilities.

5. Advanced Technology Development: Such technology is essential to the development of facilities that will remain state-of-the-art during the operating life of the Space Station. These facilities will be designed using a modular approach so that new technology can be incorporated when it becomes available. However, since by definition, advanced technology is not on a critical path of developing any particular apparatus or facility, it must take a lower priority.

Tasks one and two have highest priority at this time. Other tasks will move up in priority with time and available funding. The order of listing does not imply that all resource requirements for early tasks must be met before any resources are made available to a later task since it is necessary to maintain a balance across the program. However, in the event of a funding short fall, some reallocation will be necessary to maintain resources for the higher priority tasks at the expense of the lower priority tasks.

The primary functions of microgravity ground-based research, funded through the Research and Analysis (R & A) program, are to develop concepts that will lead to flight experiments; to determine limitations of various terrestrial processing techniques in order to define what benefits may be expected from microgravity; or to provide support to the flight program by developing characterization techniques for analyzing results of flight experiments, modelling of processes in various acceleration environments, and determining various physical properties needed for such modelling.

Priorities in the R & A program are:

1. Support of institutional commitments such as the Discipline Working Groups, Visiting Scientist Program, Centers of Excellence, and other support functions.

2. Support of existing flight programs through process modelling or measurement of physical properties needed to design experiments.

3. Support of ground-based research needed to develop new flight experiments.

4. Support of investigations directed toward filling the gaps and addressing the "critical issues" identified in the directed research program.

5. Enhancement of ground-based and suborbital facilities such as the various drop facilities, aircraft, sounding rockets, and the Microgravity Materials Science Lab.

6. Ground-based research aimed at determining the limitations imposed by gravity in various processes in order to establish a rationale for future flight experiments.

Many of the research efforts sponsored by the MSA program, especially those required of a PI developing a potential flight experiment, suggest new and innovative methods for accomplishing the same result without resorting to microgravity. In such cases, especially if a process with commercial potential is involved, the PI is referred to the OCP's Technology Utilization Office to obtain funding to continue the development of that particular process.

IMPLEMENTATION STRATEGIES

The six major microgravity program goals and their subobjectives will be achieved through the following implementation strategies.

GOAL 1:

Conduct a comprehensive research program in materials science, biotechnology, and fundamental physics, chemistry and biology through investigations in space.

A. Develop a comprehensive knowledge base incorporating research results, advances in technology, and characteristics of the microgravity environment.

- Implement procedures which ensure maintaining and improving the quality of research.
- Maintain a vigorous program of ground-based and suborbital microgravity research to clarify requirements for, and optimize results from, spaceflight experiments.
- Exploit fully the range of capabilities of the Space Shuttle, Spacelab and other NASA and commercial carriers available for microgravity flight research centered around the dedicated USML microgravity missions to be initiated in 1992.

- -- Follow an incremental approach to research in which experiments are developed on the ground, tested and refined on Shuttle flights, and where appropriate, conducted on an orbiting national microgravity laboratory.

- -- Utilize expert advisory bodies (Discipline Working Groups) and the proposed National Microgravity Science, Applications and Commercialization Task Force, made up of representatives from NASA and other federal agencies, to identify gaps in the current science program and other critical technical issues which need to be addressed.

- -- Develop and implement a microgravity communication plan to disseminate effectively research results and opportunities.

- -- Solicit and support research and applications proposals from industry, government and the academic research community that extend the scope of current investigations or introduce new fields of study.

- -- Establish a database and network for research and engineering results and information on microgravity and related programs.

B. Integrate industry-driven science requirements into the baseline research program.

- -- Expand a cooperative microgravity science and applications outreach program with industry, through the NASA Office of Commercial Programs and the Centers for the Commercial Development of Space.

- -- Establish and maintain new channels of communication among industry, academia, government and scientific advisory groups.

C. Lead the development and implementation of a National Microgravity Research Plan that establishes and maintains coordination with, and contributions from, other federal agencies.

- -- Conduct a survey of government agencies to document the level and type of interest in microgravity research.

- -- Develop a program of interagency cooperation, education, and commitment to foster a national perspective for microgravity research and applications.

- -- **Provide a mechanism for Principal Investigators funded by industry or other government agencies to extend their research efforts to microgravity.**

GOAL 2:

Expand and facilitate an interdisciplinary research community united by shared goals and resources, to conduct research in the space environment.

A. Broaden participation in the microgravity program.

- -- Develop and fund new program initiatives.
- -- Intensify use of Discipline Working Groups (DWGs) and advisory committees to provide a proponency for high-priority work.
- -- Reach a wider spectrum of the research community through outreach activities and implementation of a communications plan.
- -- Increase the participation of industry and other government agencies.

B. Maximize the timely access to flight opportunities through consideration of all flight options including secondary payloads, military missions, sounding rockets, etc.

C. Foster the development of the next generation of scientists and engineers trained in microgravity and other space-related disciplines.

- -- Develop an interdisciplinary research capability in selected research institutions to foster wider understanding and interest in microgravity research.
- -- Emphasize microgravity research in NASA support programs for education.

D. Promote interdisciplinary communication of microgravity program goals, research opportunities, and results through affiliation with major scientific and professional associations.

GOAL 3:

Establish a permanently manned, multi-facility national microgravity laboratory in low-Earth orbit to provide a long duration, stable microgravity environment. In addition to its other functions, the Space Station would also be the centerpiece of this capability.

A. Define and develop state-of-the-art experiment hardware and facilities for the microgravity research.

- Pursue the evolutionary development of multi-user, facility class hardware; refined on Spacelab for long duration deployment on the Space Station or a Commercially Developed Space Facility (CDSF).
- Identify and develop advanced technologies which significantly extend hardware capabilities.
- Develop experiment specific hardware for high value experiments and emphasize adaptable or modular hardware for experiments with similar science requirements.

B. Utilize the U.S. Laboratory Module of the Space Station as the central component of a national microgravity laboratory.

- Maintain close coordination among the Office of Space Science and Applications, the Office of Commercial Programs, the Office of Aeronautical Science and Technology, and the Office of Space Station to ensure optimum microgravity research capabilities aboard the proposed Space Station.
- Initiate a systems engineering effort for Space Station Experiment Modules.

C. Encourage effective use of commercially developed facilities and carriers as additional components of a national microgravity laboratory.

- Advocate the private sector initiatives and proposals to provide commercially developed facilities and carriers for microgravity research.

D. Provide for a national microgravity laboratory in space to be operated, to the extent technically feasible, like a National Laboratory.

- Collaborate with Office of Space Station (OSS) to develop a management plan and budget through consultation with other government agencies for a national microgravity laboratory in space.

GOAL 4:

Develop and demonstrate new technologies, materials, and processes relevant to basic research and commercial application through utilization of the space environment.

A. **Increase the understanding of the influence of gravity on Earth-based processes and materials.**

- **Produce benchmark materials in space that yield key insights to materials and processes.**
- **Initiate a pilot manufacturing technology program to identify "high leverage" processing problems.**
- **Expand the Centers for the Commercial Development of Space program into promising new areas of research in the space environment.**

B. Lay the foundations for space manufacturing.

- Initiate interaction with appropriate trade and professional associations to build an informed constituency.
- Conduct space-based production of small quantities of high-value materials.
- Develop new processes or processing techniques which are unique to microgravity.
- Explore modular processing for adaptable pilot scale production.

C. Apply telescience, automation, and robotics to microgravity and materials processing in space.

- Support the Telescience Testbed Pilot Program (TTPP) within OSSA.
- Foster a program to develop and integrate advanced technologies that facilitate space processing.

GOAL 5:

Transfer to industry the technology and "know-how" supporting new, commercially-viable products, services, and markets resulting from microgravity research.

A. Provide effective dissemination of knowledge and technology derived from microgravity research to U.S. industry.

- Utilize the Technology Utilization Office within the NASA Office of Commercial Programs.
- Facilitate technology transfer by utilizing the most effective mechanisms developed by federal research laboratories.

- -- Expand opportunities for industrial personnel to participate in flight programs, which could include industrial payload specialists.

GOAL 6:

Support, on a reimbursable basis, the launch and operation of private sector facilities and experiments. Continue to encourage the launch of microgravity research payloads by the private sector.

A. Develop new models for NASA-industry partnerships in technology development and transfer, including commercialization.

- -- Select and employ the most effective mechanisms developed by federal research laboratories and agencies to encourage commercialization of research results.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

August 19, 1988

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

In the Fiscal Year 1988 NASA Authorization Act, as passed by the House of Representatives on July 9, 1987, NASA, in cooperation with the Department of Defense (DOD), was directed to submit to Congress a five-year plan setting forth a schedule for planned reimbursements from the DOD to NASA for Space Shuttle services, as well as a schedule for the provision of such services.

The requested plan is enclosed. It is based on NASA's March 1988 Mixed Fleet Manifest developed in cooperation with the DOD. The plan projects estimated reimbursements from the DOD through Fiscal Year 1993. However, these estimates will change if the manifest itself is reconfigured either as a result of the loss of the ammonium perchlorate plant in Henderson, Nevada, or other changes being considered by the DOD.

Consistent with the language of the House-passed bill, NASA will update this five-year plan annually, submitting the plan along with the President's annual budget request.

Sincerely,

James C. Fletcher
Administrator

Enclosure

cc: Honorable Manuel Lujan, Jr.

DEPARTMENT OF DEFENSE REIMBURSEMENTS TO NASA

-BASED ON THE MARCH, 1988 NASA MIXED FLEET MANIFEST

The National Aeronautics and Space Administration (NASA) provides Space Shuttle flights to the Department of Defense for the launch of national security payloads, pursuant to an agreement between the two agencies. For the prepayment of flights prior to the January, 1986 loss of the Orbiter, Challenger, NASA is providing nine Shuttle flights in Fiscal Years 1989 - 1991.

Additional reimbursements to NASA are displayed below. Payments shown are based on a rate of $115 million (in FY 1986 dollars) for a dedicated Shuttle flight. Payments for flights beyond FY 1991 are subject to a new price to be negotiated. Payments to NASA are made no later than January of the fiscal year prior to the fiscal year of the scheduled flight.

	FY 1989	FY 1990	FY 1991	FY 1992	FY 1993	Five Year Total Estimated
DEDICATED STS FLIGHTS	3	4	2	2	2	13
SHARED STS FLIGHTS	-.-	-.-	0.66	0	0	0.66
TOTAL STS EQUIVALENT FLIGHTS	3	4	2.66	2	2	13.66
FLIGHTS PREPAID	3	4	2	-.-	-.-	9
FLIGHTS REQUIRING REIMBURSEMENT	-.-	-.-	0.66	2	2	4.66
REIMBURSEMENT DUE ('86$)	-.-	$76M	$230M	$230M	$259M*	$795M

* PAYMENT BASED ON 2.25 STS FLIGHTS PLANNED IN FY 1994

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

October 4, 1988

Honorable Bill Nelson
Chairman
Subcommittee on Space Science
and Applications
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

In accordance with P.L. 100-147 Section 112 of the NASA Authorization Act of 1988, I am most pleased to provide you with the signed English version texts of NASA's agreements for international space station cooperation. The Space Station Freedom is the largest scientific and technical venture we have ever undertaken in cooperation with our friends and allies. I am confident that it will serve as a model for international cooperation on future large-scale, high technology projects.

The documents I am providing to you today are two Memoranda of Understanding (MOU's) between NASA and its counterpart agencies in Europe and Canada. Although we have completely negotiated an MOU with Japan, Japan will be able to sign it only after its Diet has ratified the Intergovernmental Agreement (IGA), which is expected to occur in the spring of 1989. Until then, we have entered into a separate temporary arrangement with Japan which extends our space station cooperation under the provisions of an existing MOU, appropriately modified. When Japan signs the MOU, I will provide it to you in accordance with P.L. 100-147.

The Secretary of State will be providing to you, under separate cover, signed copies of the multilateral IGA among all the partners--the United States, Europe, Japan and Canada--and an Interim Arrangement among the United States, Europe and Canada. The IGA and MOU's cover cooperation among the partners in the detailed design, development, operation and utilization of the space station during the lifetime of the program. The IGA contains broad principles and government-level commitments for the cooperative space station program. The MOU's provide technical and programmatic details for the implementation of the program. The Interim Arrangement provides a legal basis for cooperation among the United States, Europe and Canada during the period between signature and entry into force of the IGA. The separate temporary arrangement with Japan, previously referred to, provides such a basis for cooperation during this period between the United States and Japan.

International cooperation on the Freedom program is a direct result of President Reagan's January 1984 invitation to U.S. friends and allies to join us in building and sharing the benefits of the permanently manned space station. Space station cooperation was subsequently endorsed at several Economic Summits and in a number of bilateral meetings between the President and his foreign counterparts. The Congress has continuously endorsed space station cooperation as reflected by the NASA Authorization Act of 1988 which directs NASA to "promote international cooperation in the space station program by undertaking the development, construction, and operation of the space station in conjunction with (but not limited to) the Governments of Europe, Japan, and Canada."

Since 1985, NASA has been cooperating with its European, Japanese and Canadian technical agency counterparts in the definition and preliminary design phase of the program. Each of the partners has now made a high-level political commitment to join the United States in the actual construction and use of this exciting endeavor. Western Europe will provide hardware worth approximately $4.2 billion; Japan, $2 billion; and Canada, $1 billion. These foreign hardware contributions will significantly enhance the overall capabilities of the core U.S. space station. In addition to hardware development contributions, the international partners will cover more than 25 percent of the annual operating costs of Freedom Station.

We have been working closely with you and your staff during the past two-and-a-half years of negotiations. The documents transmitted herewith reflect the results of a good solid working relationship that we have enjoyed with the Congress, and hope to continue in the future. Your continuing support of the Space Station Freedom program has been instrumental in making the program a standard-bearer for international cooperative programs and, for this, we are deeply appreciative.

With best regards,

Sincerely,

James C. Fletcher

James C. Fletcher
Administrator

Enclosures

cc:
Honorable Robert S. Walker

Memorandum of Understanding
Between the
United States National Aeronautics and Space Administration
and the Ministry of State for Science and Technology of Canada
on Cooperation in the
Detailed Design, Development, Operation and Utilization
# of the Permanently Manned Civil Space Station

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The National Aeronautics and Space Administration (NASA) and the Ministry of State for Science and Technology of Canada (MOSST), having successfully cooperated in the detailed definition and preliminary design of the permanently manned civil Space Station, pursuant to the April 16, 1985, Memorandum of Understanding, have agreed to continue this cooperation through its detailed design, development, operation and utilization. This cooperation was initiated by the January 1984 direction of the President of the United States to NASA to develop and place into orbit a permanently manned civil Space Station and his invitation to friends and allies of the United States to cooperate in its development and use, followed by acceptance of that invitation by the Prime Minister of Canada at the March 1985 Quebec Summit meeting with the President of the United States and the mutual confirmation of their intention to cooperate at the March 1986 Washington, D.C., Summit meeting.

The European Space Agency (ESA) and the Government of Japan (GOJ) have also agreed in Memoranda of Understanding with NASA to cooperate in the detailed design, development, operation and utilization of the permanently manned civil Space Station. The GOJ has designated the Science and Technology Agency of Japan (STA) in its Memorandum of Understanding with NASA as its Cooperating Agency, as provided for in Article 4 of the Intergovernmental Agreement. NASA and MOSST will cooperate closely with ESA and STA in the detailed design, development, operation and utilization of the Space Station.

Article 1 - Objectives of this Memorandum of Understanding

1.1. This Memorandum of Understanding implements and is intended to be consistent with the provisions of the Agreement among the Government of the United States, the Governments Members of the European Space Agency, the Government of Japan (GOJ) and the Government of Canada on Cooperation in the Detailed Design, Development, Operation, and Utilization of the Permanently Manned Civil Space Station of this date (hereinafter the "Intergovernmental Agreement").

1.2. The objectives of this Memorandum of Understanding (MOU) are:

- To provide the basis for cooperation between NASA and MOSST (hereinafter "the Parties") in the detailed design, development, operation and utilization of the Space Station for peaceful purposes, in accordance with international law
- To detail the roles and responsibilities of NASA, MOSST, ESA and STA (hereinafter "the partners") in the detailed design, development, operation and utilization of the Space Station and also to record the commitments of NASA and MOSST to each other and to ESA and STA
- To establish the management structure and interfaces necessary to ensure effective planning and coordination in the conduct of the detailed design, development, operation and utilization of the Space Station
- To provide a framework that maximizes the total capability of the Space Station to accommodate user needs and that ensures that the Space Station is operated in a manner that is safe, efficient and effective for both Space Station users and Space Station operators
- To provide a general description of the Space Station and the elements comprising it

Article 2 - General Description of the Space Station

2.1. The detailed design, development, operation and utilization of the permanently manned civil Space Station for peaceful purposes, in accordance with international law, is a long-term international cooperative endeavor, on the basis of genuine partnership, involving the Governments of the United States, Canada, certain member states of the European Space Agency and Japan. This MOU defines the nature of this genuine partnership, including the respective rights and obligations of the Parties in this cooperation.

2.2. NASA has a Space Station program which will produce a core U.S. Space Station. MOSST, ESA and STA have space programs to produce significant elements which, together with the core U.S. Space Station, will create an international Space Station complex with greater capabilities that will enhance the use of space for the benefit of all participating nations and humanity. MOSST's contribution will be an essential part of the infrastructure of the permanently manned civil international Space Station complex (hereinafter "the Space Station").

2.3. The Space Station will be a unique, multi-use facility in low-Earth orbit, comprising both manned and unmanned elements: a permanently manned base comprising elements provided by all the partners; unmanned platforms in near-polar orbit; a man-tended free-flying laboratory to be serviced at the manned base; and Space Station-unique ground elements to support the operation and utilization of the elements on orbit.

2.4. The Space Station will enable its users to take advantage of human ingenuity in connection with its low-gravity environment, the near-perfect vacuum of space and the vantage point for observing the Earth and the rest of the Universe. Specifically, the Space Station and its evolutionary additions could provide for a variety of capabilities, for example:

- a laboratory in space, for the conduct of science and applications and the development of new technologies
- a permanent observatory, with elements in low inclination and near-polar orbits, from which to observe Earth, the Solar System and the rest of the Universe
- a transportation node where payloads and vehicles are stationed, assembled, processed and deployed to their destination
- a servicing capability from which payloads and vehicles are maintained, repaired, replenished and refurbished
- an assembly capability from which large space structures and systems are assembled and verified
- a research and manufacturing capability in space, where the unique space environment enhances commercial opportunities
- an infrastructure to encourage commercial investment in space
- a storage depot for consumables, payloads and spares

- a staging base for possible future missions, such as a permanent lunar base, a manned mission to Mars, unmanned planetary probes, a manned survey of the asteroids, and a manned scientific and communications facility in geosynchronous orbit

Article 3 - Space Station Elements

3.1. The Space Station will consist of elements provided by the partners. The elements comprise both flight elements and Space Station-unique ground elements. The elements are summarized in the Annex to the Intergovernmental Agreement and are further elaborated in this Article. Their requirements are defined and controlled in appropriate program documentation as provided for in Article 7.

3.2. NASA Space Station Flight Elements: NASA will design, develop and provide the following flight elements including subsystems, the Extra Vehicular Activity (EVA) system, the Space Station Information System, flight software and spares as required:

- One permanently attached Habitation Module with complete basic functional outfitting to support habitation for a crew of up to eight, including primary storage of crew provisions

- One permanently attached multipurpose Laboratory Module, located so as to contain the center of gravity of the manned base, with complete basic functional outfitting and including provisions for storage of NASA spares, secondary storage of crew provisions, and storage for safe haven capability

- Two sets of Attached Payload Accommodation Equipment for accommodation of payloads externally attached to the manned base Truss Assembly

- Four Resource Nodes which provide pressurized volume for crew and equipment, connections between manned base pressurized elements and support of pressurized attached payloads

- Truss Assembly which is the manned base structural framework

- Solar Photovoltaic Power Modules which serve as the manned base electrical power source, providing 75kw of total power

- Propulsion Assembly

- At least three sets of Logistics Elements (pressurized and unpressurized Integrated Logistics System carriers) which provide systems operation support and user ground-to-orbit and return logistics and on-orbit supply for extended periods

- Airlock/Hyperbaric Airlock for purposes of crew and equipment transfer

- One Flight Telerobotic System (FTS)

- One Mobile Transporter which will serve to provide translation capability for the Mobile Servicing Center

- One Polar Platform to work together with the ESA-provided Polar Platform

3.3. Canadian Space Station Flight Elements: Canadian elements will be developed to play the predominant role in satisfying the following functions for the Space Station:

- attached payload servicing (external)
- Space Station assembly
- Space Station maintenance (external)
- transportation on Space Station
- deployment and retrieval functions
- EVA support

3.3.a. MOSST will design, develop and provide the following flight elements, including subsystems, flight software and spares as required:

- One Mobile Servicing Center (MSC) which comprises a Mobile Remote Servicer (MRS) and the NASA-provided Mobile Transporter

- One MSC Maintenance Depot (MMD), primarily for maintenance of the MSC, including external storage of MOSST element spares. (Necessary internal storage of MOSST element spares will be provided in the NASA-provided elements.)

- One Special Purpose Dexterous Manipulator (SPDM)

3.4. ESA and STA Space Station Flight Elements: As reflected in the MOU between NASA and ESA and in the MOU between NASA and the GOJ:

3.4.a. ESA Space Station Flight Elements: ESA will design, develop and provide the following flight elements including subsystems, flight software and spares as required:

- One Attached Pressurized Module (APM), with volume equivalent to that of four Spacelab segments, permanently attached to the manned base, with complete basic functional outfitting and including provisions for storage of ESA spares, secondary storage of crew provisions, and storage for safe haven capability

- One Polar Platform to work together with the NASA-provided Polar Platform

- One Man-Tended Free Flyer (MTFF), including a pressurized module, with volume equivalent to that of two Spacelab segments, capable of autonomous operational periods of six months or longer

3.4.b. STA Space Station Flight Elements: STA will design, develop and provide the following flight elements including subsystems, flight software and spares as required:

- One Japanese Experiment Module (JEM), a permanently attached multipurpose research and development laboratory, consisting of a pressurized module and an Exposed Facility, at least two Experiment Logistic Modules, and including a scientific equipment airlock, the JEM remote manipulator and IVA control/monitoring of the JEM Remote Manipulator System (JEM-RMS), with complete basic functional outfitting, including provisions for storage of STA spares, secondary storage of crew provisions, and storage for safe haven capability

3.5. Space Station-unique ground elements will be provided by NASA, MOSST and the other partners. These elements will be adequate to support the design and development (including assembly and verification), the continuing operation and the full international utilization of each partner's flight elements listed above. The requirements for these elements will be defined and controlled in appropriate program documentation as provided for in Article 7.

3.5.a. NASA will provide the following Space Station-unique ground elements to support the flight elements listed in Article 3.2: equipment required for specialized or unique integration or launch; ground support equipment (GSE) and flight support equipment (FSE) including necessary logistics; engineering support centers and user support centers; a polar platform control center; and test equipment, mock-ups, simulators, failities, crew training equipment and software. To support the Space Station as a whole, NASA will provide Space Station-unique ground elements including the Space Station Control Center (SSCC), the Payload Operations Integration Center (POIC), subsystem testbeds and elements related to logistics support and to software development including the Software Support Environment.

3.5.b. As will be agreed and documented in the program documentation as provided for in Article 7, MOSST will provide, at defined locations, a defined capacity of the following Space Station-unique ground elements: a user support center and, to support the MOSST flight elements listed in Article 3.3, equipment required for specialized or unique integration or, as the case may be, for launch or return to Earth; GSE and FSE including necessary logistics; engineering support centers; and test equipment, mock-ups, simulators, facilities, crew training equipment and software.

3.5.c. As reflected in the MOU between NASA and the GOJ and in the MOU between NASA and ESA, STA and ESA will provide, at defined locations, a defined capacity of the following Space Station-unique ground elements to support their flight elements listed in Article 3.4: equipment required for specialized or unique integration or, as the case may be, for launch or return to Earth; GSE and FSE including necessary logistics; engineering support centers and user support centers; and test equipment, mock-ups, simulators, facilities, crew training equipment and software.

Article 4 - Access to and Use of the Space Station

4.1. NASA and MOSST will each assure access to and use of their Space Station flight elements listed in Article 3, in accordance with allocation commitments detailed in Articles 8.3.a, 8.3.b and 8.3.c. Beyond these allocation commitments, the capabilities of the Space Station will be made available to the partners subject to specific arrangements between the relevant partners.

4.2. The partners' utilization of flight elements listed in Article 3 will be equitable, as provided in the allocation commitments set forth in Article 8 of this MOU and of the corresponding MOU's between NASA and ESA and between NASA and the GOJ.

4.3. In accordance with the procedures in Article 8, NASA and MOSST will each assure access to and use of their Space Station-unique ground elements referred to in Article 3.5 by each other and the other partners in order to support fully the utilization of the flight elements in accordance with the Consolidated Operations and Utilization Plan provided for in Article 8.1.c. As provided in Article 8, NASA and MOSST will each also assure access to and use of their Space Station-unique ground elements by each other and the other partners for system operations support.

4.4. When requested by MOSST for its design and development activities, access to and use of the Space Station-unique ground elements provided by NASA to support the Space Station as a whole will be in accordance with appropriate program documentation as provided for in Article 7. Access by NASA and MOSST to each other's remaining Space Station-unique ground elements for design and development activities will be subject to specific arrangements on a space-available basis.

Article 5 - Major Program Milestones

5.1. The Space Station programs of NASA and MOSST each include detailed design and development. The NASA and MOSST programs also include Space Station operation and utilization. Because of the extended period required to assemble the Space Station, the design and development activities will overlap the operation and utilization activities. After the completion of detailed design and development which includes assembly of the Space Station and one year of initial operational verification (Phase C/D), mature operations and utilization (Phase E) will begin.

5.2. Major target milestones for the Space Station are as follows:

- Initiation of NASA's Phase C/D	Dec 1987
- Initiation of MOSST's Phase C/D	July 1987
- First MSC Elements Delivery Date to KSC	Sep 1994
- First Space Station Element Launch	Mar 1995
- FTS Launch	June 1995
- First MSC Elements Launch	Sep 1995
- Permanently Manned Capability	Dec 1996
- SPDM Launch	Mar 1997
- Completion of Manned Base Assembly	Feb 1998
- Completion of NASA's Phase C/D; Initiation of Phase E	Feb 1999

5.3. NASA and MOSST will develop, maintain and exchange coordinated implementation schedules. These schedules, including the dates for the above milestones, the delivery dates for the MOSST-provided elements and the assembly sequence for all elements of the Space Station, will be updated as necessary and formally controlled in appropriate program documentation as provided for in Article 7.

Article 6 - Respective Responsibilities

6.1.a. While undertaking the detailed design and development of the Space Station elements described in Articles 3.2 and 3.5.a, and within the scope of the Parties' responsibilities established elsewhere in this MOU, NASA will:

1. Provide overall program coordination and direction;

2. Perform overall system engineering and integration and perform system engineering and integration for NASA-provided elements consistent with these responsibilities;

3. Design elements to be compatible with the NASA Space Transportation System (STS) and the Space Station Information System which includes the NASA Tracking and Data Relay Satellite System;

4. Establish, in consultation with the other partners, overall verification, safety, reliability, quality assurance and maintainability requirements and plans and develop verification, safety, reliability, quality assurance and maintainability requirements and plans for the NASA-provided elements that meet or exceed these overall requirements and plans, which address the elements in Articles 3.2 and 3.5.a;

5. Confirm that the MOSST verification, safety, reliability, quality assurance and maintainability requirements and plans for the MOSST-provided elements, developed by MOSST in accordance with Article 6.2.a.3 meet or exceed the overall Space Station verification, safety, reliability, quality assurance and maintainability requirements and plans;

6. Provide regular progress and status information on NASA Space Station program activities and plans;

7. Provide program information, systems requirements information and technical interface information necessary for the integration of MOSST-provided flight elements described in Article 3.3 into the Space Station; necessary to understand the impact of NASA-provided flight elements described in Article 3.2 on the MOSST-provided flight elements and their operation; and necessary for the coordinated operation and utilization of the MOSST-provded flight elements;

8. Develop, with MOSST, the agreed joint documentation described in Article 7.1;

9. Perform ground integration tests as necessary to assure on-orbit compatibility and perform verification and acceptance tests for the flight elements in Article 3.2 and accommodate MOSST representation at such tests as necessary for NASA and MOSST to fulfill their respective responsibilities under this MOU;

10. Maintain, and provide to MOSST on request, ground and on-orbit verification test procedures and results that are required to verify that the interfaces of the following elements with the MOSST-provided elements are as set forth in the documents described in Article 7.1 and to ensure that the MOSST-provided elements comply with Space Station requirements: the Mobile Transporter, the FTS, and any other flight elements in Article 3 as may be agreed by NASA and MOSST;

11. Conduct overall Space Station preliminary design reviews, critical design reviews, design certification reviews, safety, reliability and quality assurance reviews, operations readiness reviews and flight readiness reviews in order for NASA to certify, following the certifications at element level provided by NASA and the other partners, that all Space Station elements are acceptable for launch, on-orbit assembly and orbital operations, and accommodate MOSST representation as necessary for NASA and MOSST to fulfill their respective responsibilities under this MOU;

12. Conduct for the elements it provides preliminary design reviews, critical design reviews, design certification reviews and safety, reliability and quality assurance reviews; and accommodate MOSST representatives as necessary for NASA and MOSST to fulfill their respective responsiblities under this MOU;

13. Support, as appropriate, and provide information necessary for MOSST to conduct the reviews identified in Article 6.2.a.9;

14. Integrate into NASA-provided flight elements the MOSST-provided internal control station equipment for the MOSST-provided flight elements;

15. Following design and development of the NASA-provided flight elements, deliver them on-orbit in accordance with the assembly sequence controlled by appropriate program documentation as described in Article 7;

16. Deliver on-orbit the MOSST-provided elements in accordance with Article 12.1.b and the assembly sequence controlled in appropriate program documentation as provided for in Article 7; assemble on-orbit and verify interfaces of all Space Station flight elements, including the flight elements that MOSST will provide, with assistance from MOSST in accordance with agreed assembly, activation and verification plans;

17. Assist in the on-orbit activation and performance verification of flight elements provided by MOSST in accordance with agreed assembly, activation and verification plans;

18. For each NASA-provided flight element, provide necessary ground and flight support equipment and initial spares; and perform qualification and acceptance tests of this equipment according to Space Station program requirements and interfaces as set forth in the documents described in Article 7.1;

19. Establish in Canada and accommodate in the U.S. agreed liaison personnel as provided in Article 7.2;

20. Participate with MOSST and the other partners in Space Station management mechanisms as provided in Articles 7 and 8, including the development of the Operations Management Plan and the Utilization Management Plan;

21. Work with MOSST and the other partners to ensure that the Space Station Composite Utilization Plan described in Article 8.3.f can be accommodated by the elements provided by NASA, MOSST and the other partners -- in particular, work with MOSST and the other partners to establish standard interfaces between the elements and user-provided hardware and software; provide standard and special user integration and user operations support as described in Articles 8.3.e, 8.3.h, and 8.3.1 to users of the other partners or the other partners as users who are to use the NASA-provided flight elements; perform rack-level physical integration on the ground of NASA users of the accommodations elements; support and provide information necessary for MOSST to perform rack-level physical integration on the ground of MOSST users of the NASA-provided accommodations elements; plan and conduct user operations; and make available Space Station-unique ground elements to support the Space Station Composite Utilization Plan. In addition, NASA will work with MOSST and the other partners in order that MOSST may establish the capabilities to distribute data to MOSST users of the manned base directly from the NASA Tracking and Data Relay Satellite System (TDRSS) space network and to process MOSST real-time user commands to the manned base through the TDRSS space network;

22. Establish and maintain a computerized technical and management information system to work in conjunction with a compatible MOSST computerized information system in accordance with the documents described in Article 7.1;

23. Establish, in consultation with MOSST and the other partners, information format and communication standards for the system defined in 6.1.a.22;

24. Develop a Space Station Information System (SSIS) architecture for the end-to-end data transmission between the Space Station data source and the data user; establish and maintain a Software Support Environment (SSE), including necessary hardware and Space Station software standards to be established by NASA in consultation with MOSST and the other partners, to work in conjunction with a MOSST software development facility, in accordance with the documents in Article 7.1;

25. Develop and maintain flight and ground software related to elements it provides in accordance with Space Station software standards described in Article 6.1.a.24;

26. Develop an Integrated Logistics System for the manned base in accordance with the documents described in Article 7.1;

27. Provide spares for the NASA-provided elements as required to support assembly and initial operational verification;

28. Provide operations support and logistics support for the NASA-provided flight elements; and

29. Develop and provide to the System Operations Panel described in Article 8 baseline operations plans and maintenance plans for the NASA-provided elements describing routine systems capabilities and defining maintenance requirements, including logistics requirements, necessary for sustaining their functional performance.

6.1.b. Beginning upon the initiation of Space Station operations and utilization, and within the scope of the Parties' responsibilities established elsewhere in this MOU, NASA will:

1. Participate in Space Station management mechanisms and development of documentation as provided in Articles 7 and 8, and in the sharing of Space Station operations costs as provided in Article 9;

2. Provide sustaining engineering, spares, operations support and logistics support for the Space Station elements it provides;

3. Maintain overall systems engineering, integration and operations support capability for Space Station operations and utilization;

4. Provide resupply and logistics management/integration support for Space Station operations;

5. Work with MOSST and the other partners to prepare and implement plans for the integration and operation of user activities in the Space Station Consolidated Operations and Utilization Plan described in Article 8.1.c. In order to accomplish this, provide standard and special user integration and user operations support as described in Articles 8.3.e, 8.3.h, and 8.3.1; perform rack-level physical integration on the ground of NASA users of the accommodations elements; support and provide information necessary for MOSST to perform rack-level physical integration on the ground of MOSST users of NASA-provided accommodations elements; make available its Space Station-unique ground elements to support this Consolidated Plan; support planning for future utilization activities; and, using the capabilities provided for in Article 6.1.a.21, work with MOSST and the other partners so that MOSST may distribute data to MOSST users of the manned base directly from the TDRSS space network and process MOSST real-time user commands to the manned base through the TDRSS space network;

6. Provide logistics flights for the NASA-provided elements in accordance with Articles 9 and 12, and provide logistics flights for the MOSST-provided elements in accordance with Articles 9 and 12;

7. Provide the Space Station Control Center and the Payload Operations Integration Center for manned base operations control; a polar platform control center for the NASA-provided Polar Platform; and engineering support centers for the NASA-provided elements as provided in Article 8;

8. Maintain the Software Support Environment including hardware and software standards for the support of Space Station operations; and

9. Maintain its flight and ground software in accordance with the Space Station software standards described in Article 6.1.a.24.

6.2.a. While undertaking the detailed design and development of the Space Station elements which are described along with their defined functions in Articles 3.3 and 3.5.b, and within the scope of the Parties' responsibilities established elsewhere in this MOU, MOSST will:

1. Have system engineering and integration responsibilities for the MSC in accordance with the program documentation described in Article 7;

2. Design elements to be compatible with the STS and the Space Station Information System which includes use of TDRSS;

3. Develop, in consultation with NASA, verification, safety, reliability, quality assurance and maintainability requirements and plans for the MOSST-provided elements that meet or exceed the overall Space Station verification, safety, reliability, quality assurance and maintainability requirements and plans established in Article 6.1.a.4, which address the elements in Articles 3.3 and 3.5.b;

4. Provide regular progress and status information on MOSST Space Station program activities and plans;

5. Provide program information, systems requirements information and technical interface information necessary for the integration of MOSST-provided flight elements described in Article 3.3 into the Space Station; necessary to understand the impact of the MOSST-provided flight elements described in Article 3.3 on the Space Station configuration and operations; and necessary for the coordinated operation and utilization of the Space Station;

6. Develop, with NASA, the agreed joint documentation described in Article 7.1;

7. Perform ground integration tests as necessary to assure on-orbit compatibility and perform verification and acceptance tests for the flight elements in Article 3.3, and accommodate NASA representation at such tests as necessary for NASA and MOSST to fulfill their respective responsibilities under this MOU;

8. Maintain, and provide to NASA on request, ground and on-orbit verification test procedures and results as necessary to assess that the MOSST-provided flight elements comply with overall Space Station program requirements and interface requirements as set forth in the documents described in Article 7.1;

9. Conduct for the elements it provides preliminary design reviews, critical design reviews, design certification reviews and safety, reliability and quality assurance reviews and accommodate NASA representation as necessary for NASA and MOSST to fulfill their respective responsibilities under this MOU;

10. Support as appropriate, and provide information necessary for NASA to conduct, the reviews identified in Article 6.1.a.11;

11. Support, as appropriate, and provide information necessary for NASA to conduct the reviews identified in Article 6.1.a.12;

12. Following design and development of the MOSST-provided flight elements, deliver them to the Kennedy Space Center in accordance with the assembly sequence controlled by appropriate program documentation as described in Article 7;

13. Assist in the on-orbit assembly and interface verification of the MOSST-provided flight elements in accordance with agreed assembly, activation and verification plans;

14. Activate on-orbit and verify performance of the MOSST-provided elements with assistance from NASA in accordance with agreed assembly, activation and verification plans;

15. For each MOSST-provided flight element, provide necessary ground and flight support equipment and initial spares; and perform qualification and acceptance tests of this equipment according to Space Station program requirements and interfaces as set forth in the documents described in Article 7.1;

16. Establish in the United States and accommodate in Canada agreed liaison personnel as provided in Article 7.2;

17. Participate with NASA and the other partners in Space Station management mechanisms as provided in Articles 7 and 8, including the development of the Operations Management Plan and the Utilization Management Plan;

18. Work with NASA and the other partners to ensure that the Space Station Composite Utilization Plan described in Article 8.3.f can be accommodated by the elements provided by NASA, MOSST and the other partners -- in particular, work with NASA and the other partners to establish standard interfaces between the elements and user-provided hardware and software; provide standard and special user integration and user operations support as described in Articles 8.3.e, 8.3.h, and 8.3.1 to users of the other partners or the other partners as users who are to use the MOSST-provided flight elements; perform rack-level physical integration on the ground of MOSST users of the accommodations elements; plan and conduct user operations; make available Space Station-unique

ground elements to support the Space Station Composite Utilization Plan; and, if MOSST so chooses, establish the capabilities to distribute data to MOSST users of the manned base directly from the TDRSS space network and to process MOSST real-time user commands to the manned base through the TDRSS space network;

19. Establish and maintain, in accordance with the documents described in Article 7.1, a compatible computerized technical and management information system to work in conjunction with the NASA computerized information system referred to in Article 6.1.a.22; MOSST will be responsible for the provision of necessary hardware and software based on information format and communication standards established by NASA, in consultation with MOSST and the other partners;

20. Establish and maintain the necessary hardware and software for software production to work in conjunction with the Software Support Environment;

21. Develop and maintain flight and ground software related to elements it provides in accordance with Space Station software standards described in Article 6.1.a.24;

22. Provide spares for the MOSST-provided elements as required to support assembly and initial operational verification;

23. Provide operations support and logistics support for the MOSST-provided flight elements; and

24. Develop and provide to the System Operations Panel described in Article 8 baseline operations plans and maintenance plans for the MOSST-provided elements describing routine systems capabilities and defining maintenance requirements, including logistics requirements, necessary for sustaining their functional performance.

6.2.b. Beginning upon the initiation of Space Station operations and utilization, and within the scope of the Parties' responsibilities established elsewhere in this MOU, MOSST will:

1. Participate in Space Station management mechanisms and development of documentation as provided in Articles 7 and 8, and in the sharing of Space Station operations costs as provided in Article 9;

2. Provide sustaining engineering, spares, operations support and logistics support for the Space Station elements it provides;

3. Work with NASA and the other partners to prepare and implement plans for the integration and operation of user activities in the Space Station Consolidated Operations and Utilization Plan described in Article 8.1.c. In order to accomplish this, provide standard and special user integration and user operations support as described in Articles 8.3.e, 8.3.h, and 8.3.1; perform rack-level physical integration on the ground of MOSST users of the accommodations elements; make available its Space Station-unique ground elements to support this Consolidated Plan; support planning for future utilization activities; and, if MOSST so chooses, distribute data to MOSST users of the manned base directly from the TDRSS space network and process MOSST real-time user commands ~~to the~~ manned base through the TDRSS space network;

4. Arrange for logistics flights related to the MOSST-provided elements in accordance with Articles 9 and 12;

5. Provide an engineering support center for the MOSST-provided elements; and

6. Maintain its flight and ground software in accordance with the Space Station software standards described in Article 6.1.a.24.

Article 7 - Management Aspects of the Space Station Program Primarily Related to Detailed Design and Development

7.1. Management/Reviews

7.1.a. NASA and MOSST are each responsible for the management of their respective Space Station Phase C/D activities consistent with the provisions of this MOU. This Article establishes the management mechanisms to coordinate the respective Space Station design and development (including assembly and verification) activities of NASA and MOSST, to establish applicable requirements, to assure safe operations, to establish the interfaces between the Space Station elements, to review decisions, to establish schedules, to review the status of activities, to report progress and to resolve issues and technical problems as they arise.

7.1.b. The NASA/MOSST Program Coordination Committee (PCC), co-chaired by the NASA Associate Administrator for Space Station and the MOSST Deputy Secretary, Space Policy Sector, will meet periodically throughout the lifetime of the program or promptly at the request of either Party to review the Parties' respective design and development activities. The Co-Chairmen will together take those decisions necessary to assure implementation of the cooperative design and development activities related to Space Station flight elements and to Space Station-unique ground elements provided by the Parties, including, as appropriate, to design changes of the Parties' flight elements during Phase E. In taking decisions regarding design and development, the PCC will consider operation and utilization impacts, and will also consider design and development recommendations from the Multilateral Coordination Board described in Article 8.1.b. However, decisions regarding operation and utilization activities will be taken in accordance with Article 8. The Co-Chairmen will each designate their respective members and will decide on the location of meetings. If the Co-Chairmen agree that a specific design and development issue or decision requires consideration by another partner at the PCC level, the NASA/MOSST PCC may meet jointly with the NASA/ESA PCC and/or the NASA/STA PCC.

7.1.c. Multilateral Program Reviews will be organized by NASA and will meet as necessary at the request of any partner so that the Parties to this MOU and the other partners can report progress and discuss the status of their Phase C/D program activities.

7.1.d. Space Station requirements, configuration, housekeeping resource allocations for design purposes, and element interfaces; Space Station activities through the completion of assembly and initial operational verification; and other Space Station configuration control activities will be controlled by the Space Station Control Board (SSCB) chaired by NASA. MOSST will be a member of the SSCB, and of such subordinate boards thereof as may be agreed, attending and participating when these boards consider items which affect the MOSST-provided elements, interfaces between NASA-provided and MOSST-provided elements, interfaces between the MOSST-provided elements and other partner-provided elements, or the accommodation of the Composite Utilization Plan and the Composite Operations Plan described in Article 8. Decisions by the SSCB Chairman may be appealed to the PCC, although it is the duty of the SSCB Chairman to make every effort to reach consensus with MOSST rather than have issues referred to the PCC. Such appeals will be made and processed expeditiously. Pending resolution of appeals, MOSST need not proceed with the implementation of an SSCB decision as far as its provided elements are concerned; NASA may, however, proceed with an SSCB decision as far as its provided elements are concerned. NASA will be a member of the MOSST control board organization, and of such subordinate boards thereof as may be agreed, attending and participating as appropriate.

7.1.e. NASA will develop an overall Program Plan for Space Station design and development based on information provided by all the partners detailing overall program content, implementation approach and schedules. MOSST will develop a MOSST Program Plan for design and development detailing MOSST program content, implementation approach and schedules. A Joint Program Plan for design and development, signed by the NASA Associate Administrator for Space Station and the MOSST Deputy Secretary, Space Policy Sector, will cover the interrelationship between the MOSST program and the overall program. Any modification or any addition to the JPP will be approved by the PCC.

7.1.f. NASA will develop a Program Requirements Document (PRD) based on information provided by all the partners providing the programmatic basis for the overall conduct of Phase C/D. A Joint PRD (JPRD), signed by the NASA Associate Administrator for Space Station and the MOSST Deputy Secretary, Space Policy Sector, will represent the top-level requirements related to the MOSST-provided elements. The JPRD will identify the applicability to the MOSST program of all paragraphs in the PRD, including any which are added or modified. Any modification or any addition to the JPRD will be approved by the PCC.

7.1.g. NASA has developed an overall Program Definition and Requirements Document (PDRD) based on information provided by all the partners which contains requirements for Space Station flight element hardware and software and provides the technical basis for the overall conduct of Phase C/D. A Joint PDRD (JPDRD), signed by the NASA Program Director and the MOSST Program Manager, identifies the applicability to the MOSST program of all paragraphs in the PDRD including any which are added or modified. Any modification to the PDRD will be approved by the SSCB. Any modification or any addition to the co-signed JPDRD will be mutually agreed and jointly signed by the NASA Program Director and the MOSST Program Manager.

7.1.h. NASA will develop Architectural Control Documents (ACD's) which define and control the end-to-end architecture of the manned base distributed systems and control the interfaces of these systems with each other and with the flight elements. In addition, NASA will develop, in consultation with the appropriate partners, Interface Control Documents (ICD's) which control interfaces between: the flight elements comprising infrastructural elements and the flight elements comprising accommodations elements as defined in Article 8.1.d; between the flight elements comprising infrastructural elements; and, as appropriate, between any other flight elements, between flight and ground elements, or among ground elements. NASA will also develop a Baseline Configuration Document (BCD) based on information provided by all the partners which controls the configuration of the manned base, with the exception of the unique requirements affecting the design of the MOSST-provided elements, and of the NASA-provided Polar Platform. The ACD's and the BCD will be developed by the start of NASA's Phase C/D; the ICD's will be developed early in Phase C/D. Any modification or any addition to the ACD's, the BCD and the ICD's will be approved by the SSCB. Joint requirements and interface documentation will be developed by NASA and MOSST. This joint requirements and interface documentation will identify and control the applicability to the MOSST-provided elements of all requirements and interfaces in the ACD's, BCD and ICD's, including any which are modified; it will also define and control the unique requirements and interfaces affecting the design of the MOSST-provided elements. This joint requirements and interface documentation will be mutually agreed and jointly signed by the NASA Program Director and the MOSST Program Manager. Any modification or any addition to this joint requirements and interface documentation will be mutually agreed and jointly signed by the NASA Program Director and the MOSST Program Manager.

7.1.i. Program Management Reviews will be held as necessary at which the NASA Program Director and the Program Managers representing MOSST and the other partners will report on the status of their respective design and development activities, including schedule, element performance parameters and element interface requirements. These formal Program Management Reviews will be held at least quarterly and will be chaired by NASA. Less formal status reviews will be held monthly; representatives of the partners' Program Managers will attend these reviews.

7.1.j. MOSST will participate in selected NASA reviews on Space Station requirements, architecture and interfaces as defined in the JPP. Similarly, NASA will participate in selected MOSST reviews as defined in the JPP; the other partners will participate as appropriate.

7.1.k. Through participation in the above management mechanisms, NASA and MOSST agree to achieve commonality as required by the overall Space Station safety requirements as defined pursuant to Article 10. NASA and MOSST also agree to provide standard interfaces for Space Station users. Exceptions to these requirements for commonality may be agreed on a case-by-case basis between NASA and MOSST. In addition, NASA and MOSST will work through the above management mechanisms to seek agreement on a case-by-case basis regarding the use of interchangeable hardware and software in order to promote efficient and effective Space Station operation, including reducing the burden on the Space Station logistics system.

7.2. Liaison. The NASA Office of Space Station and MOSST Space Policy Sector are responsible for NASA/MOSST liaison activities. MOSST may provide representative(s) to NASA Headquarters in Washington, D.C., and NASA may provide representative(s) to MOSST in Ottawa. In order to facilitate the working relationships between the NASA Program Director and the MOSST Program Manager, MOSST will provide and NASA will accommodate MOSST liaison to the NASA Space Station Program Office. Similarly, NASA will provide and MOSST will accommodate NASA liaison to the MOSST Space Station Program Office. In addition, by mutual agreement, MOSST may provide and NASA will accommodate MOSST liaison to NASA Centers involved in the Space Station program, and NASA may provide and MOSST will accommodate liaison to other locations supporting the MOSST Space Station program. Arrangements specifying all conditions relating to the liaison relationships, will be agreed and co-signed by the Co-Chairmen of the PCC.

Article 8 - Management Aspects of the Space Station Program Primarily Related to Operations and Utilization

8.1. General

8.1.a. NASA and MOSST each have responsibilities regarding the management of their respective operations and utilization activities and the overall Space Station operations and utilization activities, in accordance with the provisions of this MOU. These activities will comprise long-range planning and top-level direction and coordination, which will be performed by the strategic-level organizations; detailed planning and support to the strategic-level organizations which will be performed by the tactical-level organizations; and implementation of these plans which will be performed by the execution-level organizations.

8.1.b. A Multilateral Coordination Board (MCB) will be established as soon as possible after the start of NASA's Phase C/D and will meet periodically over the lifetime of the program or promptly at the request of any partner with the task to ensure coordination of the activities of the partners related to the operation and utilization of the Space Station. The Parties to this MOU and the other partners will plan and coordinate activities affecting the safe, efficient and effective operation and utilization of the Space Station through the MCB, except as otherwise specifically provided in this MOU. The MCB will comprise the NASA Associate Administrator for Space Station; the MOSST Deputy Secretary, Space Policy Sector; the ESA Director of Space Station and Platforms; and the STA Director-General of the Research and Development Bureau. The NASA Associate Administrator for Space Station will chair the MCB. The Parties agree that all MCB decisions should be made by consensus. However, where consensus cannot be achieved on any specific issue within the purview of the MCB within the time required, the Chairman is authorized to take decisions. The Parties agree that, in order to protect the interests of all partners in the program, the operation and utilization of the

Space Station will be most successful when consensus is reached and when the affected partners' interests are taken into account. MCB decisions will not modify rights of the partners specifically provided in this MOU. Decisions regarding the operation and utilization of the ESA-provided elements which are separated from the manned base and which do not have effects on the manned base associated with servicing at the manned base or have effects on the STS associated with servicing by the STS will be taken by ESA, except as otherwise specifically provided in Article 8.3.

8.1.c. The MCB will establish Panels which will be responsible for the long-range strategic coordination of the operation and utilization of the Space Station, to be called the System Operations Panel and the User Operations Panel respectively, described in detail below. The MCB will develop a charter that will define the organizational relationships and responsibilities of these Panels, and the organizational relationships of these Panels with the tactical- and execution-level organizations described below. Any modifications to the charter will be approved by the MCB. The MCB will approve, on an annual basis, a Consolidated Operations and Utilization Plan (COUP) for the Space Station based on the annual Composite Operations Plan and the annual Composite Utilization Plan developed by the Panels and described below. In doing so, the MCB will be responsible for resolving any conflicts between the Composite Operations Plan and the Composite Utilization Plan which cannot be resolved by the Panels. The COUP will be prepared by the User Operations Panel and agreed to by the System Operations Panel. The charter for these Panels will also delineate the Panels' delegated responsibilities with respect to adjustment of the COUP. The COUP will be implemented by the appropriate tactical- and execution-level organizations.

8.1.d. Manned Base Hardware. The following is provided to explain the relationships between the different types of elements on the manned base which are allocated for use by the partners.

The Space Station manned base includes:

- accommodations elements; and
- infrastructural elements.

The accommodations elements are the NASA-provided Laboratory Module, the ESA-provided APM, the STA-provided JEM including the Exposed Facility and the Experiment Logistics Modules, and the NASA-provided Attached Payload Accommodation Equipment. The infrastructural elements comprise all other manned base elements, including servicing elements and other elements that produce resources which permit all manned base elements to be operated and used.

8.1.d.1. Housekeeping. Both accommodations elements and infrastructural elements will be used for assembly, for verification and for maintenance of the manned base in an operational status, and also for the storage of element spares, crew provisions and safe haven capability, with secondary storage of crew provisions to be distributed equally among the three laboratories. In such use, they are referred to, respectively, as providing:

- housekeeping accommodations; and
- housekeeping resources.

During Phase C/D, these housekeeping accommodations and housekeeping resources will be controlled in appropriate program documentation as provided for in Article 7. During Phase E, these housekeeping accommodations and housekeeping resources will be controlled according to the mechanisms in Article 8.2.d.

8.1.d.2. Utilization. The accommodations and resources not required to maintain the manned base in an operational status will be used in connection with Space Station utilization, and are referred to, respectively, as:

- user accommodations; and
- utilization resources.

Details regarding the allocation of the Space Station user accommodations and utilization resources are provided in Article 8.3. NASA and MOSST agree to seek to minimize the demands for housekeeping accommodations and housekeeping resources in order to maximize those available for utilization.

8.1.e. Platforms and MTFF. Because of the different character of the platforms and the MTFF, differentiation between accommodations and resources is not required. Mechanisms governing the operation of these elements are to be found in Article 8.2 and mechanisms governing the utilization of these elements are to be found in Article 8.3.

8.2. Operations

8.2.a. It is the goal of the Parties to this MOU to operate the Space Station in a manner that is safe, efficient and effective for both Space Station users and Space Station operators. To accomplish this, the MCB will establish, within three months of its establishment, a System Operations Panel (SOP) to coordinate strategic-level operations activities and operations planning activities as provided for in Article 8.1.c.

8.2.b. The SOP will comprise one member each from NASA, MOSST and the other partners. Members may send designated alternates to SOP meetings. In addition, each partner may call upon relevant expertise as necessary to support SOP activities. The SOP will take decisions by consensus; in the event of failure to reach consensus on any issue, the issue will be forwarded to the

MCB for resolution. In the interest of efficient management, NASA and MOSST recognize that the SOP should take the responsibility to routinely resolve all operations issues as expeditiously as possible rather than refer such issues to the MCB.

8.2.c. The SOP will develop, approve and maintain an Operations Management Plan for the operation, maintenance, and refurbishment of and logistics for the manned base, the NASA-provided Polar Platform and the ESA-provided Polar Platform insofar as these platforms have effects on the STS associated with their servicing by the STS, and the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base during Phase E. This Plan will describe relationships among the strategic, tactical and execution levels of operations management, where the strategic level is coordinated by the SOP; the tactical level, by the tactical operations organization referred to in Article 8.2.e; and the execution level, by implementing organizations and field centers. Consistent with the other provisions of this Article, the Operations Management Plan will also address operational requirements for the manned base, the NASA-provided Polar Platform and the ESA-provided Polar Platform insofar as these platforms have effects on the STS associated with their servicing by the STS, the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base, and Space Station-unique ground elements. The Operations Management Plan will provide the procedures for preparation of the baseline operations plans and maintenance plans provided for in Articles 6.1.a.29 and 6.2.a.24, annual refinements to these baseline plans, and the Composite Operations Plan described in Article 8.2.d, including procedures for adjustment of these plans as further information becomes available.

8.2.d. On an annual basis, NASA and MOSST will each provide to the SOP any significant refinements to their baseline operations plans and maintenance plans five years in advance. Using the operations and maintenance plans and these refinements provided by all of the partners, including requirements for use of Space Station-unique ground elements, the SOP will develop and approve an annual Space Station Composite Operations Plan (COP) consistent with the annual Space Station Composite Utilization Plan described in Article 8.3.f. The COP will also identify the housekeeping accommodations and housekeeping resources required for maintenance of the manned base in an operational status. Compatibility of the COP and the Composite Utilization Plan must be assured through coordination between the SOP and the User Operations Panel, described in Article 8.3.d, during the preparation and approval process.

8.2.e. NASA, with the participation of all the partners, will be responsible for integrated tactical-level activities for Space Station manned base operations. To this end, NASA will establish an integrated tactical operations organization and the other partners will participate in discharging the responsibilities of this organization. MOSST and the other partners will provide personnel to the integrated tactical operations organization who will bring expertise on the elements each provides and will participate in overall integrated tactical operations activities. NASA and MOSST will consult and agree regarding the responsibilities to be discharged by the MOSST personnel. NASA and MOSST will also consult and agree regarding the number of MOSST personnel and all administrative conditions related to these personnel. In conjunction with the integrated activities, NASA, MOSST and the other partners will each perform distributed tactical-level activities related to the elements each provides, such as system operations support planning, user support planning, logistics planning, and the accommodations assessments described in Article 8.3.h. Tactical-level activities will include planning for system operations and for user support activities across all manned base elements. Tactical-level activities for elements separated from the manned base when outside the operational Command and Control Zone (CCZ) of the STS or the manned base, as defined in the program documentation provided for in Article 7, will be performed by the element provider. However, where the same services, such as transportation, logistics and communications, are required by both the manned base and elements which are operating separated from the manned base, planning for these services will be performed by the integrated tactical operations organization.

8.2.f. Tactical Operations Plans (TOP's) for the manned base and for the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base will be developed by the tactical operations organization described in Article 8.2.e to implement the COUP. Each TOP will include Increment Plans (IP's) for a period of two years prior to launch of the STS to the manned base for a specific increment. (An increment is normally the interval between visits of the STS for the purpose of resupply in support of manned base operations and utilization as approved in the COUP.) Each IP will describe the detailed manifest of user payloads, systems support equipment and supplies needed to support the increment. Each IP will also describe changes to the complement of hardware and software to be flown during that increment and the payload and system support activities needed to carry out the activities approved in the COUP for that increment. The IP will identify the crew complement and define logistics requirements including STS interface requirements, changes to housekeeping resource requirements, changes to housekeeping accommodation requirements and communication requirements, including TDRSS use and requirements for distribution of data, to support the subject increment.

8.2.g. NASA, with the participation of all the partners, will be responsible for integrated execution-level planning and for execution of the day-to-day operation of the manned base. Subject to these NASA responsibilities, MOSST will be responsible for execution-level activities related to the elements it provides. MOSST and the other partners will participate in discharging the responsibilities of the Space Station Control Center (SSCC), established and managed by NASA, which will conduct execution-level activities and support tactical planning. MOSST and the other partners will provide personnel to the SSCC. These personnel will bring expertise on the elements that partner provides, will participate in overall SSCC-based activities, and will support real-time on-orbit activities with emphasis on the elements each provides. NASA and MOSST will consult and agree regarding the responsibilities to be discharged by the MOSST personnel. NASA and MOSST will also consult and agree regarding the number of MOSST personnel and all administrative conditions related to these personnel. In conjunction with the integrated activities, NASA, MOSST and the other partners will each perform distributed execution-level activities related to the elements each provides, such as monitoring and support of real-time systems operations. NASA, MOSST and the other partners will provide engineering support centers to perform detailed engineering assessments and real-time operations support to the SSCC required for the operational control of the manned base elements they provide. Execution-level activities for elements separated from the manned base when outside the operational CCZ of the STS or the manned base, as defined in the program documentation provided for in Article 7, will be the responsibility of the element provider. The partners may also participate in and provide personnel to other execution-level activities at other sites as agreed.

8.2.h. The International Operational Concepts Working Group (IOCWG), established by the Space Station Phase B MOU's, will continue to advise the Parties to this MOU in planning for the establishment of the SOP. Once the SOP is established, the activities of the IOCWG will end.

8.3 Utilization

8.3.a. Manned Base

8.3.a.1. NASA and MOSST will provide Space Station manned base infrastructural elements for all of the partners to use in conjunction with assembly, maintenance, operation and servicing of the Space Station elements. In recognition of MOSST's contribution, MOSST will be allocated 3% of user accommodations on the NASA, ESA and STA manned base accommodations elements. NASA and MOSST will each control the selection of users for its allocation of user accommodations on the manned base; such NASA and MOSST control of the selection of users for their allocations of user accommodations will be exercised in accordance with the procedures provided for in this MOU for developing the Composite Utilization Plan.

8.3.a.2. Allocation of manned base resources among the partners will be in accordance with the following approach.- Housekeeping resources required by all elements, and provided as noted in Article 8.1.d.1, will be set aside. The utilization resources will be allocated as follows: 20% of utilization resources will be allocated to NASA because of its Attached Payload Accommodation Equipment; 3% of utilization resources will be allocated to MOSST; the remaining utilization resources will be apportioned equally among the three laboratory modules. ESA will be allocated 50% of the utilization resources apportioned to the ESA-provided APM and STA will be allocated 50% of the utilization resources apportioned to the STA-provided JEM. NASA will be allocated 100% of the utilization resources apportioned to the NASA-provided Laboratory Module, the remaining 50% of the utilization resources apportioned to the ESA-provided APM and the remaining 50% of the utilization resources apportioned to the STA-provided JEM. The above allocation of utilization resources is to the partner, not to the elements, and may be used by the partner on any Space Station element consistent with the COP and the Composite Utilization Plan. More than this allocation of any utilization resource may be gained by each partner through barter or purchase from other partners.

8.3.a.3. MOSST's allocation of user accommodations and utilization resources will begin once the first MSC elements are verified following assembly to the manned base.

8.3.a.4. Manned base utilization resources are power, user servicing capacity, heat rejection capacity, data handling capacity, total crew time, and EVA capacity. The initial list of manned base utilization resources to be allocated is power, user servicing capacity and total crew time. All the other manned base utilization resources may be used without allocation. To support the operation and full international utilization of the Space Station manned base as defined in Article 3, NASA plans to provide the number of STS flights per year baselined by the SSCB during Phase C/D. From the total Space Station user payload capacity available on STS flights actually flown to and from the manned base each year, each partner will have the right to purchase STS launch and return services for its Space Station utilization activities, up to its allocated percentage of utilization resources. (The foregoing does not apply to STS launch and return capacity provided to and from the manned base in connection with Space Station evolutionary additions.) Similarly, the partners will have the right to purchase, up to their allocated percentage of utilization resources, TDRSS data transmission capacity available to the manned base. The User Operations Panel, defined in Article 8.3.d, will update the lists of utilization resources and allocated utilization resources as necessary as NASA and the other partners gain experience.

8.3.b. Platforms

8.3.b.1. In recognition of the fact that platforms are separate elements that do not require extensive support from the infrastructural elements of the manned base, platforms are treated separately from the manned base.

8.3.b.2. NASA and ESA will share the use of each other's polar platforms on a balanced reciprocal basis, recognizing that the two platforms may have different capabilities and that the user community may propose specific splits based on actual payloads; such proposals must be agreed to by NASA and ESA, and by MOSST with respect to its 3% utilization of the polar platforms provided for in Article 8.3.b.3, and processed by the User Operations Panel as part of the development of the Composite Utilization Plan provided in Article 8.3.f.2. NASA and ESA will also provide associated user integration and user operations support to each other and each other's users.

8.3.b.3. MOSST will be provided 3% utilization of both the NASA and ESA polar platforms together with the associated user integration and user operations support. STA may purchase, barter or enter into other arrangements for platform utilization.

8.3.c. Man-Tended Free Flyer

8.3.c.1. ESA will retain the total use of the MTFF it provides.

8.3.c.2. Notwithstanding Article 8.3.c.1, each year, NASA will have an option to purchase or barter for up to 25% of MTFF utilization at prices ESA routinely charges comparable customers.

8.3.c.3. All accommodations and resources required to service the MTFF at the manned base will come out of the allocations available to ESA for its APM as described in Article 8.3.a, unless otherwise agreed by NASA and ESA in connection with an arrangement pursuant to Article 8.3.c.2.

8.3.d. It is the goal of the Parties to use the Space Station in a safe, efficient and effective manner. To accomplish this, the MCB will establish, within three months of its establishment, a User Operations Panel (UOP), to assure the compatibility of utilization activities of the manned base, the polar platforms and use by the MTFF of manned base utilization resources and user accommodations. The UOP will comprise one member each from NASA, MOSST and the other partners. Members may send designated alternates to UOP meetings. In addition, each partner may call upon relevant expertise as necessary to support UOP activities. The UOP will take decisions by consensus; except as noted in Article 8.3.f.2, in the event of failure to reach consensus on any issue, the issue will be forwarded to the MCB for resolution. In the interest of efficient management, NASA and MOSST recognize that the UOP should take the responsibility to routinely resolve all utilization issues as expeditiously as possible rather than refer such issues to the MCB.

8.3.e. The UOP will develop, approve and maintain a Utilization Management Plan which will describe relationships among the strategic, tactical and execution levels of utilization management, where the strategic level is coordinated by the UOP; the tactical-level, by the integrated tactical operations organization described in Article 8.2.e; and the execution-level, by implementing organizations and field centers. The Plan will also establish processes for utilization of the Space Station elements, including the user support centers and other Space Station-unique ground elements provided by all the partners, consistent with Article 8.3.d; define standard user integration and user operations support; and describe the approach to distributed user integration and operations. The Plan will provide procedures for preparation of the partners' Utilization Plans and Composite Utilization Plan described in Article 8.3.f, including procedures for adjustment of these Plans as further information becomes available.

8.3.f. Utilization Plan for the Manned Base and the Polar Platforms

8.3.f.1. On an annual basis, five years in advance, NASA, MOSST and the other partners each will develop a Utilization Plan for all proposed uses of its allocation of manned base user accommodations and utilization resources, for all proposed uses of unallocated manned base utilization resources and Space Station-unique ground elements, and for all uses of the polar platforms. Each partner will satisfy the requirements of its users for storage within the user accommodations available to that partner, with the exception of temporary on-orbit storage in the Integrated Logistics System carriers in which user equipment is launched or returned to Earth as specified in the applicable Increment Plan. As regards the MTFF, the ESA Utilization Plan will include all uses of manned base user accommodations and utilization resources required to service the MTFF at the manned base, information necessary to determine whether any planned utilization of the MTFF would have effect on the manned base associated with its servicing at the manned base, and information related to Article 9.8(a) of the Intergovernmental Agreement. NASA and MOSST each will prioritize and propose appropriate schedules for the user activities in its Utilization Plan, including the use of user support centers and other Space Station-unique ground elements to support the utilization of the flight elements. These individual Utilization Plans will take into consideration all factors necessary to assure successful implementation of the user activities, including any relevant information regarding crew skills and special requirements associated with the proposed payloads.

8.3.f.2. NASA and MOSST each will forward its Utilization Plan to the UOP. Using the Utilization Plans of NASA, MOSST and the other partners, the UOP will develop the Composite Utilization

Plan (CUP), covering the use of both flight and Space Station-unique ground elements, based on all relevant factors, including each element-provider's recommendations regarding resolution of technical and operational incompatibilities among the users proposed for its elements. In its use of the Space Station, each partner will seek, through the mechanisms established in this MOU, to avoid causing serious adverse effects on use of the Space Station by the other partners. In the event of failure of the UOP to reach consensus on the utilization of the manned base and/or related Space Station-unique ground elements, the issue will be forwarded to the MCB for resolution. In the event of failure of the UOP to reach consensus on the utilization of the ESA-provided Polar Platform, ESA will take the decision, and in the event of failure of the UOP to reach consensus on the utilization of the NASA-provided Polar Platform, NASA will take the decision; however, in either event, NASA and ESA will respect the utilization rights of Canada and of each other in any such decisions.

8.3.f.3. Utilization Plans proposed by NASA, MOSST and the other partners which fall completely within their respective allocations and do not conflict operationally or technically with one another's Utilization Plans will be automatically approved. However, Articles 9.8(a), 9.8(b) and 9.11 of the Intergovernmental Agreement will apply.

8.3.g. Utilization Plan for the MTFF

8.3.g.1. The MTFF Utilization Plan will be developed and approved by ESA. As appropriate, MTFF utilization will be consistent with Articles 8.3.c.2 and 8.3.f.1.

8.3.h. Each partner will participate in integrated tactical-level planning of user activities. To this end, each partner will provide personnel to the operations organization described in Article 8.2.e. These personnel will participate in integrated tactical-level planning of user activities; they will also support the strategic-level planning of user activities. NASA and MOSST will consult and agree regarding the responsibilities to be discharged by the MOSST personnel. NASA and MOSST will also consult and agree regarding the number of MOSST personnel and all administrative conditions related to these personnel. In addition, partners providing user accommodations will be responsible for providing standard user integration and user operations support to users of other partners or other partners as users, including conducting assessments of the flow of payload integration activities for all payloads manifested in the user accommodations they provide. Accommodation assessments for individual payloads manifested in a laboratory module covering engineering, operations and software compatibility will also be performed by the partner providing that laboratory module in support of the preparation and execution of Tactical Operations Plans and Increment Plans.

Similarly, MOSST will be responsible for providing standard user integration and user operations support for users of the other partners or other partners as users of the flight elements provided by MOSST; and NASA will be responsible for providing standard user integration and user operations support for users of the other partners or other partners as users of the manned base systems/subsystems provided by NASA.

8.3.i. Each partner will participate in discharging the responsibilities of the Payload Operations Integration Center (POIC) established and managed by NASA which will be responsible for assistance to manned base users in planning and executing user activities on the manned base, for overall direction of the execution of user activities on the manned base, and for interaction with the SSCC in order to coordinate user activities with systems operations activities. Each partner will provide personnel to the POIC. NASA and MOSST will consult and agree regarding the responsibilities to be discharged by the MOSST personnel. NASA and MOSST will also consult and agree regarding the number of MOSST personnel and all administrative conditions related to these personnel. The interaction between the POIC and SSCC will be described in the Operations Management Plan. Both NASA and MOSST will provide user support centers which will function within the framework of NASA's responsibilities for the POIC. The interactions between the user support centers and the POIC will be described in the Utilization Management Plan. NASA and ESA will each be responsible, relative to the elements they provide which are separated from the manned base, for assistance to users in planning and executing user activities, for direction of the execution of user activities and for interaction with the MTFF and polar platform control centers to coordinate user and element operations activities.

8.3.j. In working out problems which may arise after the development of the COUP, in the case of a technical or operational incompatibility between users, the partner(s) providing the element(s) in which the users have accommodations, as well as other impacted partners, will provide appropriate analyses and recommendations to the appropriate strategic-, tactical- or execution-level organization for resolution of conflicts. However, if such conflict only has impacts within a single manned base element and only impacts users of the provider of that element, the partner providing that manned base element will be responsible for resolving such conflicts in accordance with the content of the COUP; conflicts related to proposed polar platform utilization will be resolved as provided in Article 8.3.f.2.

8.3.k. NASA, MOSST and the other partners may at any time barter for, sell to one another or enter into other arrangements for any portion of their Space Station allocations, and are free to market the use of their allocations individually or collectively, according to the procedures established in the Utilization

Management Plan. The terms and conditions of any barter or sale will be determined on a case-by-case basis by the parties to the transaction. The partner providing allocations will ensure that the obligations it has undertaken under this MOU are met. NASA, MOSST and the other partners each may retain the revenues they derive from such marketing.

8.3.l. NASA and MOSST will make their Space Station-unique ground elements, including user support centers, available for use by each other and the other partners in order to support fully both the standard and special user integration and operations support approved in the CUP and the requirements in the COP. Any special user integration or user operations support provided by a partner to users of the other partners or other partners as users will be provided on a reimbursable basis at prices routinely charged comparable users for similar services.

8.3.m. The International Utilization Coordination Working Group (IUCWG), established by the Space Station Phase B MOU's, will continue to advise the Parties to this MOU in planning for the establishment of the UOP. Once the UOP is established, the activities of the IUCWG will end.

8.4. In order to protect the intellectual property of Space Station users, procedures covering all personnel, including Space Station crew, who have access to data will be developed by the MCB.

8.5. The partners will seek to outfit the NASA-provided Laboratory Module, the ESA-provided APM and the STA-provided JEM to equivalent levels by the end of Space Station assembly in Phase C/D.

Article 9 - Operations Costs Responsibilities

9.1. The Parties will seek to minimize operations costs for the Space Station. The Parties will also seek to minimize the exchange of funds, for example, through the performance of specific operations activities.

9.1.a. The costs associated with MOSST's providing personnel to undertake integrated tactical- and execution-level activities, as provided for in Articles 8.2.e, 8.2.g, 8.3.h and 8.3.i, will be agreed between NASA and MOSST and will be a contribution towards the satisfaction of MOSST's common system operations costs responsibilities established below.

9.2 Element operations costs

9.2.a. NASA and MOSST will each have operational responsibilities for the elements it provides as detailed in Article 8. Such operational responsibilities mean that NASA and

MOSST will each be financially responsible for element operations costs, that is, costs attributed to operating and to sustaining the functional performance of the flight elements that it provides, such as ground-based maintenance, sustaining engineering, provision of spares, launch and return costs for spares, launch and return costs of the fraction of the Integrated Logistics System carriers provided for in Article 3.2 that is attributable to spares, and also costs attributed to the maintenance and operation of element-unique ground centers.

9.3. Common system operations costs

9.3.a. Manned Base. Other than the element operations costs covered in Article 9.2.a, NASA, MOSST and the other partners will equitably share the common system operations costs; that is, the costs attributed to the operation of the Space Station as a whole. The categories comprising common system operations costs are: integrated tactical planning activities performed by the integrated tactical operations organization provided for in Article 8.2.e, including user integration planning and maintenance of common documentation; space systems operations (SSCC-based operations, SSCC maintenance and common elements of the Software Support Environment); POIC-based operations and POIC maintenance; Integrated Logistics System operations, including consumables and common inventory management activities; prelaunch/postlanding processing of logistics carriers; launch to orbit and return of consumables, crew and crew logistics, and launch and return of the fraction of the Integrated Logistics System carriers provided for in Article 3.2 that is attributable to consumables and crew logistics; and transmission of housekeeping data between the manned base and the ground (SSCC, POIC and launch and landing sites). Each partner will be responsible for a percentage of common system operations costs equal to the percentage of Space Station utilization resources allocated to it in Article 8.3.a.2. MOSST's responsibility for sharing common system operations costs will begin when MOSST begins to utilize the manned base once the first MSC elements are verified following assembly to the manned base, as provided in Article 8.3.a.3. If MOSST chooses to delay beginning its utilization of the manned base beyond this point, its responsibility for sharing common system operations costs will begin when it begins using user accommodations or utilization resources but in no event later than the beginning of Phase E.

9.3.b. Platforms. NASA and ESA will each be responsible for the common system operations costs for the platforms which they provide.

9.3.c. Man-Tended Free Flyer. ESA will be responsible for the common system operations costs for the MTFF it provides.

9.3.d Any changes to the list of common system operations costs in this Article will be made by agreement among the partners.

9.4. The Parties to this MOU and the other partners will work through the SOP to identify the detailed contents to be included in each common system operations cost category. The partners will also, each year, report to the SOP on their forecasts for future years for all costs included in the common system operations costs of the Space Station and on their identified actual annual common system operations costs. The SOP will develop detailed procedures for implementing this Article. If possible, after the partners have gained experience in the operation of the Space Station, the SOP will endeavor to establish a fixed value for the annual common system operations costs.

9.5. Costs of user activities such as payload/experiment design, development, test and evaluation (DDT&E), payload ground processing; provision of payload/experiment spares and associated equipment; launch and return of payloads/experiments, spares and associated equipment; launch and return of the portion of the Integrated Logistics System carriers provided in Article 3.2 that is attributable to user payloads/experiments, spares and associated equipment; and any special user integration or user operations support, including specialized crew training, will be the responsibility of Space Station users of the partners or of individual partners as users. Such costs will not be shared among NASA, MOSST and the other partners, nor will such costs contribute toward the satisfaction of common system operations costs responsibilities. In addition, the DDT&E and operations costs of the users' support centers will not be shared among NASA, MOSST and the other partners.

9.6. NASA, MOSST and the other partners will not recoup their DDT&E costs for their elements from one another in the operation and utilization of the Space Station.

9.7. In case of failure of any partner to perform its operations responsibilities or to provide for its share of common system operations costs, the partners will meet to discuss what action should be taken. Such actions could result in, for example, an appropriate reduction of the failing partner's rights to its allocations.

Article 10 - Safety

10.1. In order to assure safety, NASA has the responsibility, working with the other partners, to establish overall Space Station safety requirements and plans covering Phase C/D and Phase E. Such requirements and plans for Phase C/D have been established, and development of further safety requirements and plans for Phase C/D and Phase E and changes to safety requirements and plans will be processed according to the procedures in Articles 7 and 8.

10.2. Each partner will develop detailed safety requirements and plans, using its own standards where practicable, for its Space Station hardware and software that meet or exceed the overall Space Station safety requirements and plans. Each partner will have the responsibility to implement applicable overall and detailed Space Station safety requirements and plans throughout the lifetime of the program, and to certify that such safety requirements and plans have been met with respect to the elements and payloads it provides. NASA will have the overall responsibility to certify that all Space Station elements and payloads are safe.

10.3. NASA will conduct system safety reviews which MOSST will support. NASA, MOSST and the other partners will also conduct safety reviews of the elements and payloads they provide; NASA will participate in and support such reviews by the other partners. MOSST will also participate in and support safety reviews by the other partners as appropriate related to the MOSST-provided elements and MOSST payloads. NASA and MOSST support to safety reviews will include the provision of necessary safety-related information to enable the other partners to conduct their reviews. Furthermore, status reports on safety requirements and plans will be a standard agenda item at the Program Management Reviews provided for in Article 7.1.i. The partners will participate as appropriate in any Space Station safety review boards established by NASA.

10.4. NASA will have the responsibility for taking any decision necessary to protect the safety of the Space Station or its crew in an emergency.

Article 11 - Space Station Crew

11.1. MOSST has the right to provide personnel to serve as Space Station crew from the time that MOSST begins to share common system operations costs as provided in Article 9.3.a. NASA will provide flight opportunities for MOSST Space Station crew satisfying the percentage of the total crew requirement equal to the percentage of manned base utilization resources allocated to MOSST in Article 8.3.a.2. Flight of MOSST Space Station crew will be satisfied over time, not necessarily on each specific crew rotation cycle. The SOP will review the implementation of this paragraph on a biennial basis.

11.2. Beyond NASA's commitment in Article 11.1, during assembly and verification, a fully trained MOSST crew member will participate, as agreed between NASA and MOSST, in the on-orbit assembly and system verification of the MOSST-provided flight elements and other assigned flight element assembly and system verification tasks planned during that on-orbit period as provided in the verification plan described in Articles 6.1.a.4 and 6.2.a.3.

11.3. Space Station crew will meet medical standards and security and suitability requirements developed by NASA in consultation with MOSST and the other partners regarding Space Station crew qualifications for long-term manned space flight. NASA and MOSST will jointly certify that these standards and requirements have been met by the MOSST Space Station crew. Furthermore, the MCB may establish additional criteria for Space Station crew. Following certification, all Space Station crew will enter into an appropriate training cycle in order to acquire the skills necessary to conduct Space Station operations and utilization. Such training will be conducted in groups, subject to the requirements of different functional specializations. The training will include integrated manned systems operations training conducted primarily at NASA centers and element-specific operations training conducted primarily by the partner providing the element at appropriate centers of all of the partners. In full consultation with MOSST regarding the flight assignments of MOSST crew members, NASA will designate, from among the certified Space Station crew, specific crew complements, which include the Space Station Commander, for specific crew rotation cycles, consistent with Article 11.1. NASA will designate specific crew complements to support payload requirements identified in the COUP. A specific crew complement will be trained as a team in preparation for a specific crew rotation cycle, subject to requirements of different functional specializations.

11.4. NASA and MOSST will be financially responsible for all compensation, medical expenses, subsistence costs on Earth, and training for Space Station crew which they provide. Full training for all assigned duties will be required.

11.5. The Code of Conduct for the Space Station will be developed by NASA, with the full involvement of MOSST, ESA and the GOJ, and approved for the Space Station program in accordance with the principles for reaching decisions established in Article 8.1.b. It will, *inter alia*: establish a clear chain of command; set forth standards for work and activities in space, and, as appropriate, on the ground; establish responsibilities with respect to elements and equipment; set forth disciplinary regulations; establish physical and information security guidelines; and provide the Space Station Commander appropriate authority and responsibility, on behalf of all the partners, to enforce safety procedures and physical and information security procedures in or on the Space Station.

Article 12 - Transportation, Communications and Other Non-Space Station Facilities

12.1. Transportation

12.1.a. For purposes of design of Space Station elements and payloads, NASA's STS is the baseline launch and return transportation system for the Space Station manned base and for the NASA-provided Polar Platform.

12.1.b. NASA will be responsible for standard STS launch services in connection with the assembly of the MOSST-provided elements to the manned base. (MOSST will be responsible for any optional STS launch services required in connection with the assembly of the MOSST-provided elements to the manned base.) NASA will provide reimbursable launch and return services in connection with the logistics requirements of manned base elements. NASA will also provide reimbursable launch and return services in connection with Space Station users; availability of STS services for this purpose is as provided in Article 8.3.a.4. Reimbursement for such launch services may be in cash or agreed kind. All reimbursable STS services will be provided under launch services agreements. NASA will also provide launch and return services in connection with manned base common system operations logistics; costs for such services will be shared among the partners as provided in Article 9.3. In the development of Space Station operation and utilization plans, NASA will use its best efforts to accommodate additional launch and return requirements in relation to the Space Station, as well as proposed requirements and flight schedules.

12.1.c. Other government or private sector space transportation systems of partners may be used in connection with the Space Station if they are compatible with the Space Station, as provided in the MOU's with ESA and STA.

12.1.d. With respect to financial conditions, NASA will provide reimbursable launch and return services to MOSST, to the other partners, and to MOSST's and the other partner's users at prices it routinely charges comparable users. Launch and return services related to manned base common system operations logistics will also be made available by NASA on the same basis.

12.1.e. Each partner will respect the proprietary rights in and confidentiality of appropriately marked data and goods to be transported on its space transportation system.

12.2. Communications

12.2.a. Space Station communications will involve space-to-ground, ground-to-ground and space-to-space data transmission. The TDRSS space network is the baseline communication system for the manned base elements and payloads, as well as for the NASA-provided Polar Platform and its payloads. ESA's Data Relay Satellite system (EDRS) is the baseline communication system for the ESA-provided Polar Platform and MTFF and their payloads. On a reimbursable basis, NASA and ESA will use their best efforts to accommodate, with their respective communication systems, specific Space Station-related requirements of MOSST and the other partners. With respect to financial conditions, NASA and ESA will provide such communication services at prices no higher than those they routinely charge comparable customers. Other communication systems may be used on the manned base by MOSST, the other partners or Space Station users if such communication systems are compatible with the manned base and manned base use of TDRSS. Technical and operational requirements related to Space Station communications will be controlled in appropriate program documentation as provided for in Articles 7 and 8.

12.2.b. Unless otherwise agreed by NASA and ESA, ground-to-ground transmission of polar platform data from one partner to the other partners or the other partners' users will conform to the communications transportation formats, protocols and standards agreed to by the Consultative Committee for Space Data Systems (CCSDS).

12.2.c. Partners and users of the partners may implement measures to ensure confidentiality of their utilization data passing through the Space Station Information System and other communication systems being used in connection with the Space Station. (Notwithstanding the foregoing, data which are necessary to assure safe operations will be made available according to procedures in the Utilization Management Plan and their use will be restricted to safety purposes only.) Each partner will respect the proprietary rights in, and the confidentiality of, the utilization data passing through its communication systems, including its ground network and the communication systems of its contractors, when providing communication services to another partner.

12.3. Other Non-Space Station Facilities

12.3.a. Should MOSST desire to use the Space Shuttle, Spacelab, or other NASA facilities on a cooperative or reimbursable basis to support the development of its Space Station Utilization Plan or to support its Space Station detailed design or development activities, NASA will use its best efforts to accommodate MOSST's proposed requirements and schedules. Likewise, should NASA desire to use MOSST facilities on a cooperative or reimbursable basis to support the development of its Space Station Utilization Plan or to support its Space Station detailed design or development activities, MOSST will use its best efforts to accommodate NASA's proposed requirements and schedules.

12.3.b. If NASA and MOSST agree that it is appropriate and necessary for the conduct of the cooperative program, NASA and MOSST will use their good offices in connection with attempting to arrange for the use of U.S. and Canadian Governments' or contractors' facilities by the Parties and/or their contractors. Such use will be subject to separate arrangements between the user and the owner of the facilities.

Article 13 - Advanced Development Program

13.1. NASA and MOSST each are conducting Space Station advanced development programs in support of their respective detailed design and development activities. Cooperation in such advanced development activities will be considered on a case-by-case basis and entered into where it is advantageous to both sides and where there are reciprocal opportunities.

13.2. MOSST proposals to use NASA advanced development test beds or other NASA facilities in support of MOSST's Space Station advanced development program will be considered on a case-by-case basis either on a cooperative or reimbursable basis. Likewise, NASA proposals to use MOSST's facilities in support of NASA's Space Station advanced development program will be considered on a case-by-case basis either on a cooperative or reimbursable basis.

13.3. Should MOSST desire to use the Space Shuttle or Spacelab on a cooperative or reimbursable basis to support MOSST Space Station advanced development activities, NASA will use its best efforts to accommodate MOSST's proposed requirements and flight schedules.

Article 14 - Space Station Evolution

14.1. The partners intend that the Space Station will evolve through the addition of capability and will strive to maximize the likelihood that such evolution will be effected through contributions from all the partners. To this end, it will be the object of the Parties to provide, where appropriate, the opportunity to the other partners to cooperate in their respective proposals for additions of evolutionary capability. The Space Station together with its additions of evolutionary capability will remain a civil station, and its operation and utilization will be for peaceful purposes, in accordance with international law.

14.2. This MOU sets forth rights and obligations concerning only the elements listed in Article 3, except that this Article and Article 16 of the Intergovernmental Agreement will apply to any additions of evolutionary capability. As such, this MOU does not commit either Party to participate in, or grant either Party rights in, the addition of evolutionary capability.

14.3. NASA and MOSST agree to study evolution concepts for the Space Station during Phase C/D and Phase E. NASA will be responsible for development of overall Space Station evolution concepts, in consultation with MOSST and the other partners, and for integrating MOSST's and the other partners' evolution concepts into an overall Space Station evolution plan.

14.4. NASA, MOSST, and the other partners will participate in an International Evolution Working Group (IEWG) to coordinate their respective evolution studies and to consider overall Space Station evolution concepts and planning activities.

14.5. The MCB will review specific evolutionary capabilities proposed by any partner, assess the impacts of those plans on the other partners' elements and on the manned base, and review recommendations for minimizing potential impacts on Space Station activity during the addition of evolutionary capabilities.

14.6. Following the review and assessment provided for in Article 14.5, and consistent with the provisions of the Intergovernmental Agreement, cooperation between or among partners regarding the sharing of addition(s) of evolutionary capability will require either amendment of the relevant NASA-MOSST, NASA-ESA and NASA-GOJ MOU's or a separate agreement to which, to the extent that such addition is on the manned base or has a technical or operational impact on the STS or the manned base, NASA is a party to ensure that such addition is consistent with NASA's overall programmatic responsibilities as detailed in this MOU.

14.7. Following the review and assessment provided for in Article 14.5, and consistent with the provisions of the Intergovernmental Agreement, the addition of evolutionary capability by one partner will require prior notification of the other partners, and, to the extent that such addition is on the manned base or has a technical or operational impact on the STS or the manned base, an agreement with NASA to ensure that such addition is consistent with NASA's overall programmatic responsibilities as detailed in this MOU.

14.8. The addition of evolutionary capability will in no event alter the rights and obligations of either Party to this MOU concerning the elements listed in Article 3, unless otherwise agreed by the affected Party.

Article 15 - Cross-Waiver of Liability; Exchange of Data and Goods; Treatment of Data and Goods in Transit; Customs and Immigration; Intellectual Property; Criminal Jurisdiction

The Parties note that, with respect to the cross-waiver of liability, exchange of data and goods, treatment of data and goods in transit, customs and immigration, intellectual property and criminal jurisdiction, the relevant provisions of the Intergovernmental Agreement apply.

Article 16 - Financial Arrangements

16.1. Each Party will bear the costs of fulfilling its responsibilities, including but not limited to costs of compensation, travel and subsistence of its own personnel and transportation of all equipment and other items for which it is responsible. However, as provided in Article 9.3, the partners will equitably share common system operations costs.

16.2. The ability of each Party to carry out its obligations is subject to its funding procedures and the availability of appropriated funds.

16.3. In the event that funding problems arise that may affect a partner's ability to fulfill its responsibilities under this MOU, that partner will promptly notify and consult with the other partners.

16.4. The Parties will seek to minimize the exchange of funds while carrying out their respective responsibilities in this cooperative program, including, if they agree, through the use of barter, that is, the provision of goods or services.

Article 17 - Public Information

17.1. NASA and MOSST will be responsible for the development of an agreed Public Affairs Plan that will specify guidelines for NASA/MOSST cooperative public affairs activities during the detailed design, development, operation and utilization of the Space Station.

17.2. Within the Public Affairs Plan guidelines, both NASA and MOSST will retain the right to release public information on their respective portions of the program. NASA and MOSST will undertake to coordinate with each other, and, as appropriate, with the other partners, in advance concerning public information activities which relate to each other's responsibilities or performance in the Space Station program.

Article 18 - Consultation and Settlement of Disputes

18.1. The Parties agree to consult with each other and with the other partners promptly when events occur or matters arise which may occasion a question of interpretation or implementation of the terms of this MOU.

18.2. In the case of a question of interpretation or implementation of the terms of this MOU, such question will be first referred to the NASA Associate Administrator for Space Station and the MOSST Deputy Secretary, Space Policy Sector, for settlement. The Parties recognize that in the case of a question concerning the commitments made in this MOU to ESA and/or STA, the consultations will be broadened so as to include the ESA Director of Space Station and Platforms and/or the STA Director-General of the Research and Development Bureau.

18.3. Any question of interpretation or implementation of the terms of this MOU which has not been settled in accordance with Article 18.2 will be referred to the NASA Administrator and the

Secretary of MOSST for settlement. The Parties recognize that in case of a question concerning the commitments made in this MOU to ESA and/or STA, the matter will also be referred to the Director General of ESA and/or the Minister of State for Science and Technology of Japan.

18.4. Any issues arising out of this MOU not satisfactorily settled through consultation pursuant to this Article may be pursued in accordance with the relevant provisions of the Intergovernmental Agreement.

18.5. Unless otherwise agreed between NASA and MOSST, implementation of decisions made pursuant to mechanisms provided for in this MOU will not be held in abeyance pending settlement of issues under this Article.

Article 19 - Entry into Force; Withdrawal

19.1. This MOU will become effective after signature of both the NASA Administrator or his designee and the Minister of State (Science and Technology) of Canada, upon written notification by each Party to the other that all procedures necessary for its becoming effective have been completed.

19.2. If the United States or Canada withdraws from the Arrangement Concerning Application of the Space Station Intergovernmental Agreement Pending its Entry into Force, which became effective on September 29, 1988, the corresponding Cooperating Agency will be deemed to have withdrawn from this MOU effective from the same date.

19.3. If, by December 31, 1992, the Intergovernmental Agreement has not yet entered into force between the United States and Canada in accordance with Article 25 of that Agreement, the Parties will consider what steps are necessary and appropriate to take account of that circumstance.

19.4. If the United States or Canada gives notice of withdrawal from the Intergovernmental Agreement in accordance with Article 27 of that Agreement, the corresponding Cooperating Agency will be deemed to have withdrawn from this MOU effective from the same date.

Article 20 - MOU Amendments

This MOU may be amended at any time by written agreement of the Parties. Any amendment must be consistent with the Intergovernmental Agreement. To the extent that a provision of this MOU creates specific rights or obligations accepted by another partner, that provision may be amended only with the written consent of that partner.

Article 21 - Review

Upon the request of either Party, the Parties will meet for the purpose of reviewing and promoting cooperation in the Space Station. In the process of this review, the Parties may consider amendments to this MOU.

Article 22 - Definitions and Explanations

22.1. The following definitions will apply to this MOU:

"international Space Station complex," also "Space Station," means the collection of elements listed in Article 3;

"manned base" means Space Station flight elements excluding the polar platforms and the MTFF;

"Parties" means NASA and MOSST;

"partners" means NASA, MOSST, ESA and STA.

22.2. Explanation of the following terms may be found in this MOU in the Articles noted:

"Accommodations" - Article 8.1.d
"Common system operations costs" - Article 9.3
"Composite Operations Plan (COP)" - Article 8.2.d
"Composite Utilization Plan (CUP)" - Article 8.3.f
"Consolidated Operations and Utilization Plan (COUP)" - Article 8.1.c
"Flight elements" - Article 3
"Infrastructure" - Article 8.1.d
"Multilateral Coordination Board (MCB)" - Article 8.1.b
"Program Coordination Committee (PCC)" - Article 7.1.b
"Resources" - Article 8.1.d and Article 8.3.a.4
"Space Station Control Board (SSCB)" - Article 7.1.d
"Space Station-unique ground elements" - Article 3
"System Operations Panel (SOP)" - Article 8.2.a and Article 8.2.b
"User Operations Panel (UOP)" - Article 8.3.d

DONE at Washington, this 29th day of September, 1988, in two originals in the English and French languages, each version being equally authentic.

FOR THE UNITED STATES
NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION:

POUR L'ADMINISTRATION NATIONALE
DE L'AERONAUTIQUE ET DE
L'ESPACE DES ETATS-UNIS:

Dale D Myers

FOR THE MINISTRY OF STATE
FOR SCIENCE AND TECHNOLOGY
OF CANADA:

POUR LE MINISTERE D'ETAT
DES SCIENCES ET DE LA
TECHNOLOGIE DU CANADA:

Memorandum of Understanding
Between the
United States National Aeronautics and Space Administration
and the European Space Agency
on Cooperation in the Detailed Design,
Development, Operation and Utilization of the
Permanently Manned Civil Space Station

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The National Aeronautics and Space Administration (hereinafter "NASA") and the European Space Agency, (hereinafter "ESA"),

Recalling that in his State of the Union Address of January 25, 1984, the President of the United States directed NASA to develop and place into orbit within a decade a permanently manned Space Station and invited friends and allies of the United States to participate in its development and use and to share in the benefits thereof, in order to promote peace, prosperity and freedom,

Recalling the terms of Resolution Number 2 adopted on 31 January 1985 by the ESA Council meeting at ministerial level on participation in the Space Station program,

Recalling the terms of Resolution Number 2 adopted on 10 November 1987 by the ESA Council meeting at ministerial level on participation in the Space Station program,

Recalling the NASA Administrator's letter of April 6, 1984, to the ESA Director General,

Having successfully implemented the Memorandum of Understanding between NASA and ESA for the Conduct of Parallel Detailed Definition and Preliminary Design Studies (Phase B) Leading toward Further Cooperation in the Development, Operation and Utilization of a Permanently Manned Space Station, which entered into force on June 3, 1985,

Considering the Agreement among the Government of the United States of America, Governments of Member States of the European Space Agency, the Government of Japan and the Government of Canada on Cooperation in the Detailed Design, Development, Operation and Utilization of the Permanently Manned Civil Space Station (hereinafter "the Intergovernmental Agreement") and particularly Article 4 thereof, Considering the Memorandum of Understanding between NASA and the Science and Technology Agency of Japan (STA) for the Cooperative Program Concerning Detailed Definition and Preliminary Design Activities of a Permanently Manned Space Station, which entered into force on May 9, 1985, and the Memorandum of Understanding between NASA and the Ministry of State for Science and Technology of Canada (MOSST), for a Cooperative Program Concerning Detailed Definition and Preliminary Design (Phase B) of a Permanently Manned Space Station, which entered into force on April 16, 1985,

Considering the Memorandum of Understanding between NASA and the Government of Japan (the GOJ) on Cooperation in the Detailed Design, Development, Operation and Utilization of the Permanently Manned Civil Space Station and recognizing that the GOJ has designated STA in that Memorandum of Understanding as its Cooperating Agency, as provided for in Article 4 of the Intergovernmental Agreement,

Considering also the Memorandum of Understanding between NASA and MOSST on Cooperation in the Detailed Design, Development, Operation and Utilization of the Permanently Manned Civil Space Station,

Convinced that this cooperation among NASA, ESA, STA and MOSST implementing the provisions established in the Intergovernmental Agreement will further expand cooperation through the establishment of a long-term and mutually beneficial relationship and will further promote cooperation in the exploration and peaceful use of outer space,

Have agreed as follows:

Article 1 - Purpose and Objectives

1.1. The purpose of this Memorandum of Understanding (MOU) is, pursuant to Article 4 of the Intergovernmental Agreement and on the basis of genuine partnership, to establish arrangements between NASA and ESA (hereinafter "the Parties") implementing the provisions of the Intergovernmental Agreement concerning the detailed design, development, operation and utilization of the permanently manned civil Space Station for peaceful purposes, in accordance with international law. In drafting this MOU, the Parties intended it to be consistent with the provisions of the Intergovernmental Agreement. This MOU will be subject to the provisions of the Intergovernmental Agreement. It defines the nature of the genuine partnership, including the respective rights and obligations of the Parties to this MOU.

1.2. The specific objectives of this MOU are:

- to detail the roles and responsibilities of NASA, ESA, STA and MOSST (hereinafter the "partners") in the detailed design, development, operation and utilization of the Space Station and also to record the commitments of NASA and ESA to each other and to STA and MOSST;
- to establish the management structure and interfaces necessary to ensure effective planning and coordination in the conduct of the detailed design, development, operation and utilization of the Space Station;
- to provide a framework that maximizes the total capability of the Space Station to accommodate user needs and that ensures that the Space Station is operated in a manner that is safe, efficient and effective for both Space Station users and Space Station operators; and
- to provide a general description of the Space Station and the elements comprising it.

1.3. Relevant definitions and explanations are to be found in Article 22.

Article 2 - General Description of the Space Station

2.1. NASA has a Space Station program which will produce a core U.S. Space Station. ESA has a Columbus program, and STA and MOSST also have space programs to produce significant elements which, together with the core U.S. Space Station, will create an international Space Station complex with greater capabilities that will enhance the use of space for the benefit of all participating nations and humanity. MOSST's contribution will be an essential part of the infrastructure of the permanently manned civil international Space Station complex (hereinafter "the Space Station").

2.2. The Space Station will be a unique, multi-use facility in low-Earth orbit, comprising both manned and unmanned elements: a permanently manned base comprising elements provided by all the partners; unmanned platforms in near-polar orbit; a man-tended free-flying laboratory to be serviced at the manned base; and Space Station-unique ground elements to support the operation and utilization of the elements on orbit.

2.3. The Space Station will enable its users to take advantage of human ingenuity in connection with its low-gravity environment, the near-perfect vacuum of space and the vantage point for observing the Earth and the rest of the Universe. Specifically, the Space Station and its evolutionary additions could provide for a variety of capabilities, for example:

- a laboratory in space, for the conduct of science and applications and the development of new technologies;
- a permanent observatory, with elements in low inclination and near-polar orbits, from which to observe Earth, the Solar System and the rest of the Universe;
- a transportation node where payloads and vehicles are stationed, assembled, processed and deployed to their destination;
- a servicing capability from which payloads and vehicles are maintained, repaired, replenished and refurbished;
- an assembly capability from which large space structures and systems are assembled and verified;
- a research and manufacturing capability in space, where the unique space environment enhances commercial opportunities;
- an infrastructure to encourage commercial investment in space;
- a storage depot for consumables, payloads and spares; and
- a staging base for possible future missions, such as a permanent lunar base, a manned mission to Mars, unmanned planetary probes, a manned survey of the asteroids, and a manned scientific and communications facility in geosynchronous orbit.

Article 3 - Space Station Elements

3.1. The Space Station will consist of elements comprising both flight elements and Space Station-unique ground elements. The elements are summarized in the Annex to the Intergovernmental Agreement and are further elaborated in this Article. Their requirements are defined and controlled in appropriate program documentation as provided for in Article 7.

3.2. NASA Space Station Flight Elements: NASA will design, develop and provide the following flight elements including subsystems, the Extra Vehicular Activity (EVA) system, the Space Station Information System, flight software and spares as required:

- one permanently attached Habitation Module with complete basic functional outfitting to support habitation for a crew of up to eight, including primary storage of crew provisions

- one permanently attached multipurpose Laboratory Module, located so as to contain the center of gravity of the manned base, with complete basic functional outfitting and including provisions for storage of NASA spares, secondary storage of crew provisions, and storage for safe haven capability

- two sets of Attached Payload Accommodation Equipment for accommodation of payloads externally attached to the Space Station Truss Assembly

- four Resource Nodes which provide pressurized volume for crew and equipment, connections between manned base pressurized elements and support of pressurized attached payloads

- Truss Assembly which is the manned base structural framework

- Solar Photovoltaic Power Modules which serve as the manned base electrical power source, providing 75kw of total power

- Propulsion Assembly

- at least three sets of Logistics Elements (pressurized and unpressurized Integrated Logistics System carriers) which provide systems operation support and user ground-to-orbit and return logistics and on-orbit supply for extended periods

- Airlock/Hyperbaric Airlock for purposes of crew and equipment transfer

- one Flight Telerobotic System (FTS)

- one Mobile Transporter which will serve to provide translation capability for the Mobile Servicing Center

- one Polar Platform to work together with the ESA-provided Polar Platform

3.3. ESA Space Station Flight Elements: ESA will design, develop and provide the following flight elements including subsystems, flight software and spares as required:

- one Attached Pressurized Module (APM), with volume equivalent to that of four Spacelab segments, permanently attached to the manned base, with complete basic functional outfitting and including provisions for storage of ESA spares, secondary storage of crew provisions, and storage for safe haven capability

- one Polar Platform to work together with the NASA-provided Polar Platform

- one Man-Tended Free Flyer (MTFF), including a pressurized module, with volume equivalent to that of two Spacelab segments, capable of autonomous operational periods of six months or longer.

3.4. STA and MOSST Space Station Flight Elements: As reflected in the MOU between NASA and the GOJ and in the MOU between NASA and MOSST:

3.4.a. STA Space Station Flight Elements: STA will design, develop and provide the following flight elements including subsystems, flight software and spares as required:

- one Japanese Experiment Module (JEM), a permanently attached multipurpose research and development laboratory, consisting of a pressurized module and an Exposed Facility, at least two Experiment Logistic Modules, and including a scientific equipment airlock, the JEM remote manipulator and IVA control/monitoring of the JEM Remote Manipulator System (JEM-RMS), with complete basic functional outfitting, including provisions for storage of STA spares, secondary storage of crew provisions, and storage for safe haven capability

3.4.b. MOSST Space Station Flight Elements: Canadian elements will be developed to play the predominant role in satisfying the following functions for the Space Station:

- attached payload servicing (external)
- Space Station assembly
- Space Station maintenance (external)
- transportation on Space Station
- deployment and retrieval functions
- EVA support

3.4.b.1. MOSST will design, develop and provide the following flight elements, including subsystems, flight software and spares as required:

- one Mobile Servicing Center (MSC) which comprises a Mobile Remote Servicer (MRS) and the NASA-provided Mobile Transporter

- one MSC Maintenance Depot (MMD), primarily for maintenance of the MSC, including external storage of MOSST element spares. (Necessary internal storage of MOSST element spares will be provided in the NASA-provided elements.)

- one Special Purpose Dexterous Manipulator (SPDM)

3.5. Space Station-unique ground elements will be provided by NASA, ESA and the other partners. These elements will be adequate to support the design and development (including assembly and verification), the continuing operation and the full international utilization of each partner's flight elements listed above. The requirements for these elements will be defined and controlled in appropriate program documentation as provided for in Article 7.

3.5.a. NASA will provide the following Space Station-unique ground elements to support the flight elements listed in Article 3.2: equipment required for specialized or unique integration or launch; ground support equipment (GSE) and flight support equipment (FSE) including necessary logistics; engineering support centers and user support centers; a polar platform control center; and test equipment, mock-ups, simulators, crew training equipment, software and any facilities necessary to house these items. To support the Space Station as a whole, NASA will provide Space Station-unique ground elements including the Space Station Control Center (SSCC), the Payload Operations Integration Center (POIC), subsystem testbeds and elements related to logistics support and to software development including the Software Support Environment.

3.5.b. As will be agreed and documented in the program documentation as provided for in Article 7, ESA will provide, at defined locations, a defined capacity of the following Space Station-unique ground elements to support the ESA flight elements listed in Article 3.3: equipment required for specialized or unique integration or, as the case may be, for launch or return to Earth; GSE and FSE including necessary logistics; operations control centers, engineering support centers and user support centers; and test equipment, mock-ups, simulators, crew training equipment, software and any facilities necessary to house these items.

3.5.c. As reflected in the MOU between NASA and the GOJ and in the MOU between NASA and MOSST, STA and MOSST will provide, at defined locations, a defined capacity of the following Space

Station-unique ground elements to support their flight elements listed in Article 3.4: equipment required for specialized or unique integration or, as the case may be, for launch or return to Earth; GSE and FSE including necessary logistics; engineering support centers and user support centers; and test equipment, mock-ups, simulators, crew training equipment, software and any facilities necessary to house these items.

Article 4 - Access to and Use of the Space Station

4.1. NASA and ESA will each assure access to and use of their Space Station flight elements listed in Article 3, in accordance with allocation commitments detailed in Articles 8.3.a, 8.3.b, and 8.3.c. Beyond these allocation commitments, the capabilities of the Space Station will be made available to the partners subject to specific arrangements between the relevant partners.

4.2. The partners' utilization of flight elements listed in Article 3 will be equitable, as provided in the allocation commitments set forth in Article 8 of this MOU and of the corresponding MOU's between NASA and the GOJ and between NASA and MOSST.

4.3. In accordance with the procedures in Article 8, NASA and ESA will each assure access to and use of their Space Station-unique ground elements referred to in Article 3.5 by each other and the other partners in order to support fully the utilization of the flight elements in accordance with the Consolidated Operations and Utilization Plan provided for in Article 8.1.c. As provided in Article 8, NASA and ESA will each also assure access to and use of their Space Station-unique ground elements by each other and the other partners for system operations support.

4.4. As requested by ESA for its design and development activities, access to and use of the Space Station-unique ground elements provided by NASA to support the Space Station as a whole will be provided for in appropriate program documentation as provided for in Article 7. Access by ESA and NASA to each other's remaining Space Station-unique ground elements for design and development activities will be subject to specific arrangements on a space-available basis.

Article 5 - Major Program Milestones

5.1. The Space Station program of NASA and the Columbus program of ESA each include detailed design and development. The NASA and ESA programs also include Space Station operation and utilization. Because of the extended period required to assemble the Space Station, the design and development activities will overlap the operation and utilization activities. After the completion of detailed design and development which includes assembly of the Space Station and one year of initial operational verification (Phase C/D), mature operations and utilization (Phase E) will begin.

5.2. Major target milestones for the Space Station are as follows:

- Initiation of NASA's Phase C/D	Dec 1987
- Initiation of ESA's Phase C/D	Feb 1988
- NASA-provided Polar Platform Preliminary Design Review	Jan 1989
- First Space Station Element Launch	Jan 1994
- NASA-provided Laboratory Module Launch	Jan 1995
- Permanently Manned Capability	Oct 1995
- NASA-provided Polar Platform Launch	Oct 1995
- ESA-provided APM Launch	Oct 1996
- Completion of Manned Base Assembly	Nov 1996
- ESA-provided Polar Platform Launch	Mar 1997
- Completion of NASA's Phase C/D; Initiation of Phase E	Nov 1997
- First Station Servicing of MTFF	Jun 1998

5.3. NASA and ESA will develop, maintain and exchange coordinated implementation schedules. These schedules, including the dates for the above milestones, the delivery dates for the ESA-provided elements and the assembly sequence for all elements of the Space Station, will be updated as necessary and formally controlled in appropriate program documentation as provided for in Article 7.

Article 6 - Respective Responsibilities

6.1.a. While undertaking the detailed design and development of the Space Station elements described in Articles 3.2 and 3.5.a, and within the scope of the Parties' responsibilities established elsewhere in this MOU, NASA will:

1. provide overall program coordination and direction;
2. perform overall system engineering and integration and perform system engineering and integration for NASA-provided elements consistent with these responsibilities;
3. establish, in consultation with the other partners, overall verification, safety, reliability, quality assurance and maintainability requirements and plans and develop verification, safety, reliability, quality assurance and maintainability requirements and plans for the NASA-provided elements that meet or exceed these overall requirements and plans, which address the elements in Articles 3.2 and 3.5.a;
4. confirm that the ESA verification, safety, reliability, quality assurance and maintainability requirements and plans for the APM, for the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base, and for the ESA-provided Polar Platform insofar as it has effects on the NASA Space Transportation System (STS) associated with its servicing by the STS, developed by ESA in accordance with Article 6.2.a.5, meet or exceed the overall Space Station verification, safety, reliability, quality assurance and maintainability requirements and plans;
5. provide regular progress and status information on NASA Space Station program activities and plans;
6. provide, as applicable, program information, systems requirements information and technical interface information necessary for the integration of ESA-provided elements described in Article 3.3 into the Space Station and/or the coordinated operation and utilization of ESA-provided elements;
7. develop, with ESA, the agreed joint documentation described in Article 7.1;
8. perform ground integration tests as necessary to assure on-orbit compatibility and perform verification and acceptance tests for the flight elements in Article 3.2 and accommodate ESA representation at such tests as necessary for NASA and ESA to fulfill their respective responsibilities under this MOU;
9. conduct overall Space Station preliminary design reviews, critical design reviews, design certification

reviews, safety, reliability and quality assurance reviews, operations readiness reviews and flight readiness reviews in order for NASA to certify, following the certifications at element level provided by NASA and the other partners, that: all Space Station elements to be launched on the STS, including the ESA-provided APM, are acceptable for launch, on-orbit assembly and orbital operations; that the ESA-provided Polar Platform, to be launched on Ariane-5, is acceptable for servicing by STS; and that the ESA-provided MTFF, to be launched by Ariane-5, is acceptable for servicing at the manned base; and accommodate ESA representation as necessary for NASA and ESA to fulfill their respective responsibilities under this MOU;

10. conduct for the elements it provides preliminary design reviews, critical design reviews, design certification reviews, and safety, reliability and quality assurance reviews; and accommodate ESA representatives as necessary for NASA and ESA to fulfill their respective responsibilities under this MOU;

11. support, as appropriate, and provide information necessary for ESA to conduct the reviews identified in Article 6.2.a.11;

12. deliver on-orbit the ESA-provided APM and its initial outfitting in accordance with Article 12 and the assembly sequence controlled in appropriate program documentation as provided for in Article 7; assemble on-orbit and verify interfaces of Space Station flight elements, including the flight elements that ESA will provide, with assistance from ESA, in accordance with agreed assembly, activation and verification plans;

13. assist in the on-orbit activation and performance verification of the APM provided by ESA in accordance with agreed assembly, activation and verification plans;

14. for each NASA-provided flight element, provide necessary ground and flight support equipment and initial spares; and perform qualification and acceptance tests of this equipment according to Space Station program requirements and interfaces as set forth in the documents described in Article 7.1;

15. establish in Europe and accommodate in the U.S. agreed liaison personnel as provided in Article 7.2;

16. participate with ESA and the other partners in Space Station management mechanisms as provided in Articles 7 and 8, including the development of the Operations Management Plan and the Utilization Management Plan;

17. work with ESA and the other partners to ensure that the Space Station Composite Utilization Plan described in Article 8.3.f. can be accommodated by the elements provided by NASA, ESA and the other partners -- in particular, work with ESA and the other partners to establish standard interfaces between the elements and user-provided hardware and software; provide standard and special user integration and user operations support as described in Articles 8.3.e, 8.3.h, and 8.3.1 to users of the other partners or the other partners as users who are to use the NASA-provided flight elements; perform rack-level physical integration on the ground of NASA users of the APM; plan and conduct user operations; and make available Space Station-unique ground elements to support the Space Station Composite Utilization Plan. In addition, NASA will work with ESA in order that NASA and MOSST, respectively, may establish the capabilities to distribute data to NASA and MOSST users of the APM directly from the NASA Tracking and Data Relay Satellite System (TDRSS) space network and to process NASA and MOSST user commands to the APM through the TDRSS space network;

18. establish in consultation with ESA and the other partners, information format and communication standards for a technical and management information system, and establish and maintain a computerized technical and management information system. This system is to work in conjunction with a compatible ESA computerized information system in accordance with the documents described in Article 7.1;

19. develop a Space Station Information System (SSIS) architecture for the end-to-end data transmission between the Space Station data source and the data user; establish and maintain a Software Support Environment (SSE), including necessary hardware and Space Station software standards to be established by NASA in consultation with ESA and the other partners, to work in conjunction with an ESA software development facility, in accordance with the documents described in Article 7.1;

20. develop and maintain flight and ground software related to elements it provides in accordance with Space Station software standards described in Article 6.1.a.19;

21. develop an Integrated Logistics System for the manned base in accordance with the documents described in Article 7.1;

22. provide spares for the NASA-provided elements as required to support assembly and initial operational verification;

23. provide operations support and logistics support for the NASA-provided flight elements; and

24. develop and provide to the System Operations Panel described in Article 8 baseline operations plans and maintenance plans for the NASA-provided elements describing routine systems capabilities and defining maintenance requirements, including logistics requirements, necessary for sustaining their functional performance.

6.1.b. Beginning upon the initiation of Space Station operations and utilization, and within the scope of the Parties' responsibilities established elsewhere in this MOU, NASA will:

1. participate in Space Station management mechanisms and development of documentation as provided in Articles 7 and 8, and in the sharing of Space Station operations costs as provided in Article 9;

2. provide sustaining engineering, spares, operations support and logistics support for the Space Station elements it provides;

3. maintain overall systems engineering, integration and operations support capability for Space Station operations and utilization;

4. provide resupply and logistics management/integration support for Space Station operations;

5. work with ESA and the other partners to prepare and implement plans for the integration and operation of user activities in the Space Station Consolidated Operations and Utilization Plan described in Article 8.1.c. In order to accomplish this, provide standard and special user integration and user operations support as described in Articles 8.3.e, 8.3.h, and 8.3.1; perform rack-level physical integration on the ground of NASA users of the APM; make available its Space Station-unique ground elements to support this Consolidated Plan; support planning for future utilization activities; and, using the capabilities provided for in Article 6.1.a.17, NASA and MOSST, respectively, may distribute data to NASA and MOSST

users of the APM directly from the TDRSS space network and process NASA and MOSST user commands to the APM through the TDRSS space network;

6. provide logistics flights for the NASA-provided elements in accordance with Articles 9 and 12, and provide logistics flights for the ESA-provided elements in accordance with Articles 9 and 12;

7. provide the Space Station Control Center and the Payload Operations Integration Center for manned base operations control; a polar platform control center for the NASA-provided Polar Platform; and engineering support centers for the NASA-provided elements as provided in Article 8;

8. maintain the Software Support Environment including hardware and software standards for the support of Space Station operations;

9. maintain its flight and ground software in accordance with the Space Station software standards described in Article 6.1.a.19;

10. upon completion of manned base assembly plus a one-year operational verification period, provide docking, access and servicing for the MTFF at the manned base as required by ESA, however, no more frequently than once every six months; and

11. if appropriate STS capability exists, provide for STS servicing of the NASA-provided Polar Platform and, if ESA selects to use this STS capability and with details to be agreed by NASA and ESA, provide STS servicing of the ESA-provided Polar Platform in accordance with Articles 9 and 12.

6.2.a. While undertaking the detailed design and development of the Space Station elements described in Articles 3.3 and 3.5.b, and within the scope of the Parties' responsibilities established elsewhere in this MOU, ESA will:

1. perform system engineering and integration for the APM consistent with NASA's overall system engineering and integration responsibilities;

2. design the APM to be compatible with the STS and with the Space Station Information System which includes use of TDRSS;

3. design and develop the ESA-provided MTFF; insofar as the MTFF has effects on the manned base associated with its

servicing at the manned base, the design and development of the MTFF will comply with otherwise established manned base requirements, capabilities and interfaces, including safety; the MTFF will be capable of autonomous operational periods of six months or longer;

4. design and develop the ESA-provided Polar Platform; insofar as the ESA-provided Polar Platform has effects on the STS associated with its servicing by the STS, its design and development will comply with the operational and safety requirements of the STS;

5. develop, in consultation with NASA, verification, safety, reliability, quality assurance and maintainability requirements and plans for the APM, for the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base, and for the ESA-provided Polar Platform insofar as it has effects on the STS associated with its servicing by the STS that meet or exceed the overall Space Station verification, safety, reliability, quality assurance and maintainability requirements and plans established in Article 6.1.a.3, which address the elements in Articles 3.3 and 3.5.b;

6. provide regular progress and status information on Columbus Program activities and plans;

7. provide, as applicable, program information, systems requirements information and technical interface information necessary to understand the impact of the ESA-provided flight elements on the Space Station configuration and/or on the coordinated operation and utilization of the Space Station, and necessary to integrate those flight elements into the Space Station;

8. develop, with NASA, the agreed joint documentation described in Article 7.1;

9. perform interface verification tests as necessary to assure on-orbit compatibility and perform verification and acceptance tests for the flight elements in Article 3.3, and accommodate NASA representation at such tests as necessary for NASA and ESA to fulfill their respective responsibilities under this MOU;

10. maintain, and provide to NASA on request, ground and on-orbit verification test procedures and results as necessary to assess that the ESA-provided APM complies with overall Space Station program requirements and interface requirements, and, insofar as they have effects on the STS and the manned base, that the

ESA-provided Polar Platform and MTFF comply with the operational and safety requirements associated with servicing of these ESA-provided elements by the STS and at the manned base, respectively, as set forth in the documents described in Article 7.1;

11. conduct for the elements it provides preliminary design reviews, critical design reviews and other reviews as set forth in the documents described in Article 7.1 which will include review of safety, reliability and quality assurance, and accommodate NASA representation as necessary for NASA and ESA to fulfill their respective responsibilities under this MOU;

12. support as appropriate, and provide information necessary for NASA to conduct, the reviews identified in Article 6.1.a.9;

13. support, as appropriate, and provide information necessary for NASA to conduct the reviews identified in Article 6.1.a.10;

14. following design and development of the APM, arrange for the on-orbit delivery of the APM and its initial outfitting in accordance with Article 12 and in accordance with the assembly sequence controlled by appropriate program documentation as described in Article 7;

15. launch and operate the MTFF so that its first servicing at the manned base will be no earlier than the completion of the one-year manned base operational verification period, and launch and operate the ESA-provided Polar Platform;

16. assist in the on-orbit assembly and interface verification of the ESA-provided APM in accordance with agreed assembly, activation and verification plans;

17. activate on-orbit and verify performance of the ESA-provided APM, with assistance from NASA, in accordance with agreed assembly, activation and verification plans; activate on-orbit and verify performance of the ESA-provided MTFF, in accordance with the appropriate program documentation as described in Article 7 which addresses the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base; and activate on-orbit and verify performance of the ESA-provided Polar Platform;

18. for each ESA-provided flight element, provide necessary ground and flight support equipment and initial spares;

and perform qualification and acceptance tests of this equipment according to Space Station program requirements and interfaces as set forth in the documents described in Article 7.1;

19. establish in the United States and accommodate in Europe agreed liaison personnel as provided in Article 7.2;

20. participate with NASA and the other partners in Space Station management mechanisms as provided in Articles 7 and 8, including the development of the Operations Management Plan and the Utilization Management Plan;

21. work with NASA and the other partners to ensure that the Space Station Composite Utilization Plan described in Article 8.3.f can be accommodated by the elements provided by NASA, ESA and the other partners -- in particular, work with NASA and the other partners to establish standard interfaces between the elements and user-provided hardware and software; provide standard and special user integration and user operations support as described in Articles 8.3.e, 8.3.h, and 8.3.1 to users of the other partners or the other partners as users who are to use the ESA-provided flight elements; support and provide information necessary for NASA and MOSST to perform rack-level physical integration on the ground of NASA and MOSST users of the APM; plan and conduct user operations; make available Space Station-unique ground elements to support the Space Station Composite Utilization Plan; and support and provide information necessary for NASA and MOSST, respectively, to establish the capabilities to distribute data to NASA and MOSST users of the APM directly from the TDRSS space network and to process NASA and MOSST user commands to the APM through the TDRSS space network;

22. establish and maintain, in accordance with the documents described in Article 7.1, a compatible computerized technical and management information system to work in conjunction with the NASA computerized information system referred to in Article 6.1.a.18; ESA will be responsible for the provision of necessary hardware and software based on information format and communication standards established by NASA, in consultation with ESA and the other partners;

23. establish and maintain the necessary hardware and software for software production to work in conjunction with the Software Support Environment;

24. develop and maintain flight and ground software related to elements it provides; for the ESA-provided APM, the development and maintenance of this software will be in accordance with Space Station software standards described in Article 6.1.a.19;

25. provide spares for the ESA-provided elements as required to support initial operational verifications, including assembly for the APM;

26. provide operations support and logistics support for the ESA-provided flight elements; and

27. develop and provide to the System Operations Panel described in Article 8 baseline operations plans and maintenance plans describing routine systems capabilities and defining maintenance requirements, including logistics requirements, necessary for sustaining the functional performance of the ESA-provided APM, for the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base and for the ESA-provided Polar Platform insofar as it has effects on the STS associated with its servicing by the STS.

6.2.b. Beginning upon the initiation of Space Station operations and utilization, and within the scope of the Parties' responsibilities established elsewhere in this MOU, ESA will:

1. participate in Space Station management mechanisms and development of documentation as provided in Articles 7 and 8, and in the sharing of Space Station operations costs as provided in Article 9;

2. provide sustaining engineering, spares, operations support and logistics support for the Space Station elements it provides;

3. work with NASA and the other partners to prepare and implement plans for the integration and operation of user activities in the Space Station Consolidated Operations and Utilization Plan described in Article 8.1.c. In order to accomplish this, provide standard and special user integration and user operations support as described in Articles 8.3.e, 8.3.h, and 8.3.1; support and provide information necessary for NASA and MOSST to perform rack-level physical integration on the ground of NASA and MOSST users of the APM; make available its Space Station-unique ground elements to support this Consolidated Plan; support planning for future utilization activities; and support and provide information necessary for NASA and MOSST, respectively, to distribute data to NASA and MOSST users of the APM

directly from the TDRSS space network and to process NASA and MOSST user commands to the APM through the TDRSS space network;

4. arrange for logistics flights related to the ESA-provided elements in accordance with Articles 9 and 12;

5. provide Operations Control Centers and engineering support centers for the ESA-provided APM, Polar Platform and MTFF, as provided in Article 8; and

6. maintain its flight and ground software for the elements it provides; for the ESA-provided APM, the maintenance of this software will be in accordance with Space Station software standards described in Article 6.1.a.19.

Article 7 - Management Aspects of the Space Station Program Primarily Related to Detailed Design and Development

7.1. Management/Reviews

7.1.a. NASA and ESA are each responsible for the management of their respective Space Station Phase C/D activities consistent with the provisions of this MOU. This Article establishes the management mechanisms to coordinate the respective Space Station design and development (including assembly and verification) activities of NASA and ESA, to establish applicable requirements, to assure safe operations, to establish the interfaces between the Space Station elements, to review decisions, to establish schedules, to review the status of activities, to report progress and to resolve issues and technical problems as they arise.

7.1.b. The NASA/ESA Program Coordination Committee (PCC), co-chaired by the NASA Associate Administrator for Space Station and the ESA Director of Space Station and Platforms, will meet periodically throughout the lifetime of the program or promptly at the request of either Party to review the Parties' respective design and development activities. The Co-Chairmen will together take those decisions necessary to assure implementation of the cooperative design and development activities related to Space Station flight elements and to Space Station-unique ground elements provided by the Parties, including, as appropriate, to design changes of the Parties' flight elements during Phase E. In taking decisions regarding design and development, the PCC will consider operation and utilization impacts, and will also consider design and development recommendations from the Multilateral Coordination Board described in Article 8.1.b. However, decisions regarding operation and utilization activities will be taken in accordance with Article 8. The Co-Chairmen will each designate their respective members and will decide on the location of meetings. If the Co-Chairmen agree that a specific design and development issue or decision requires consideration by another partner at the PCC level, the NASA/ESA PCC may meet jointly with the NASA/STA PCC and/or the NASA/MOSST PCC.

7.1.c. Multilateral Program Reviews will be organized by NASA and will meet as necessary at the request of any partner so that the Parties to this MOU and the other partners can report progress and discuss the status of their Phase C/D program activities.

7.1.d. The manned base and NASA-provided Polar Platform requirements, configuration, housekeeping resource allocations for design purposes, and element interfaces will be controlled by the Space Station Control Board (SSCB) chaired by NASA. The SSCB will also control Space Station activities through the completion of assembly and initial operational verification, and other Space Station configuration control activities related to the manned base, related to the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base, and related to the ESA-provided Polar Platform insofar as it has effects on the STS associated with its servicing by the STS. ESA will be a member of the SSCB, and of such subordinate boards thereof as may be agreed, attending and participating when these boards consider items which affect the APM, interfaces between the NASA-provided and the ESA-provided elements, interfaces between the ESA-provided elements and the STS, interfaces between the ESA-provided elements and other partner-provided elements, or the accommodation on the manned base of the Composite Utilization Plan and the Composite Operations Plan described in Article 8. Decisions by the SSCB Chairman may be appealed to the PCC, although it is the duty of the SSCB Chairman to make every effort to reach consensus with ESA rather than have issues referred to the PCC. Such appeals will be made and processed expeditiously. Pending resolution of appeals, ESA need not proceed with the implementation of an SSCB decision as far as its provided elements are concerned; NASA may, however, proceed with an SSCB decision as far as its provided elements are concerned. NASA will be a member of the Columbus Control Board chaired by ESA, and of such subordinate boards thereof as may be agreed, attending and participating as appropriate. As far as the elements separated from the manned base are concerned, NASA will assume management responsiblity for the design and development of the NASA-provided Polar Platform, including meeting requirements related to polar platform user interfaces and polar platform STS servicing; ESA will assume management responsibility for the design and development of the ESA-provided Polar Platform, including meeting requirements related to polar platform user interfaces and polar platform STS servicing; ESA will also assume management responsibility for the design and development of the MTFF and for meeting requirements related to its effects on the manned base associated with its servicing at the manned base.

7.1.e. NASA will develop an overall Program Plan for Space Station design and development based on information provided by all the partners detailing overall program content, implementation approach and schedules. ESA will develop a Columbus Program Plan for design and development detailing ESA program content, implementation approach and schedules. A Joint Program Plan for design and development, signed by the NASA Associate Administrator for Space Station and the ESA Director of Space Station and Platforms, will cover the interrelationship between the ESA program and the overall program. Any modification or any addition to the JPP will be approved by the PCC.

7.1.f. NASA will develop a Program Requirements Document (PRD) based on information provided by all the partners providing the programmatic basis for the overall conduct of Phase C/D. A Joint PRD (JPRD), signed by the NASA Associate Administrator for Space Station and the ESA Director of Space Station and Platforms, will represent the top-level requirements related to the APM, the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base and the ESA-provided Polar Platform insofar as it has effects on the STS associated with its servicing by the STS. The JPRD will identify the applicability to the ESA program of all paragraphs in the PRD, including any which are added or modified. Any modification or any addition to the JPRD will be approved by the PCC.

7.1.g. NASA has developed an overall Program Definition and Requirements Document (PDRD) based on information provided by all the partners which contains requirements for Space Station flight element hardware and software and provides the technical basis for the overall conduct of Phase C/D. A Joint PDRD (JPDRD), signed by the NASA Program Director and the ESA Program Manager, contains the detailed requirements related to the APM, the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base and the ESA-provided Polar Platform insofar as it has effects on the STS associated with its servicing by the STS. The JPDRD identifies the applicability to the ESA program of all paragraphs in the PDRD including any which are added or modified. Any modification to the PDRD will be approved by the SSCB. Any modification or any addition to the co-signed JPDRD will be mutually agreed and jointly signed by the NASA Program Director and the ESA Program Manager.

7.1.h. NASA will develop Architectural Control Documents (ACD's) which define and control the end-to-end architecture of the manned base distributed systems and control the interfaces of these systems with each other and with the flight elements. In addition, NASA will develop, in consultation with the appropriate partners, Interface Control Documents (ICD's) which control interfaces between: the flight elements comprising infrastructural elements and the flight elements comprising accommodations elements as defined in Article 8.1.d; between the flight elements comprising infrastructural elements; and, as appropriate, between any other flight elements, between flight and ground elements or among ground elements. NASA will also develop a Baseline Configuration Document (BCD) based on information provided by all the partners which controls the configuration of the manned base and of the NASA-provided Polar Platform. The ACD's and the BCD will be developed by the start of NASA's Phase C/D; the ICD's will be developed early in Phase C/D. Any modification or any addition to the ACD's, the BCD and the ICD's will be approved by the SSCB. Joint interface documentation, which identifies the applicability to the ESA-provided APM of all interfaces in the ACD's, BCD and ICD's, including any which are modified, will be developed by NASA and ESA. This joint interface documentation will be mutually agreed and jointly signed by the NASA Program Director and the ESA Program Manager. Any modification or any addition to this joint interface documentation will be mutually agreed and jointly signed by the NASA Program Director and the ESA Program Manager. NASA and ESA will jointly develop an ICD which will govern the interfaces between the ESA-provided MTFF and the manned base in connection with the docking, access and servicing of the MTFF at the manned base, in accordance with Article 6.2.a.3. NASA and ESA will also jointly develop an ICD in which they will agree on standard user interfaces for the polar platforms they provide; this ICD will also govern the interfaces between the ESA-provided Polar Platform and the STS. The MTFF ICD will be developed early in Phase C/D; the Polar Platform ICD will be established no later than the Preliminary Design Review for the NASA-provided Polar Platform. The MTFF and Polar Platform ICD's will be mutually agreed and jointly signed by the NASA Program Director and the ESA Program Manager. Any modification or addition to these documents will be mutually agreed and jointly signed by the NASA Program Director and the ESA Program Manager.

7.1.i. Program Management Reviews will be held as necessary at which the NASA Program Director and the Program Managers representing ESA and the other partners will report on the status of their respective design and development activities, including schedule, element performance parameters and element interface requirements. These formal Program Management Reviews will be held at least quarterly and will be chaired by NASA. Less formal status reviews will be held monthly; representatives of the partners' Program Managers will attend these reviews.

7.1.j. ESA will participate in selected NASA reviews on Space Station requirements, architecture and interfaces as defined in the JPP. Similarly, NASA will participate in selected ESA reviews as defined in the JPP; the other partners will participate as appropriate.

7.1.k. Through participation in the above management mechanisms, NASA and ESA agree to achieve commonality on the manned base as required by the overall Space Station safety requirements as defined pursuant to Article 10. NASA and ESA also agree to provide standard interfaces for Space Station users both in the permanently attached pressurized laboratories and on the polar platforms. Exceptions to these requirements for commonality may be agreed on a case-by-case basis between NASA and ESA. In addition, NASA and ESA will work through the above management mechanisms to seek agreement on a case-by-case basis regarding the use of interchangeable hardware and software in order to promote efficient and effective Space Station operations, including reducing the burden on the Space Station logistics system.

7.2. Liaison. The NASA Office of Space Station and ESA Space Station and Platforms Directorate are responsible for NASA/ESA liaison activities. ESA may provide representative(s) to NASA Headquarters in Washington, D.C., and NASA may provide representative(s) to ESA Headquarters in Paris. In order to facilitate the working relationships between the NASA Program Director and the ESA Program Manager, ESA will provide and NASA will accommodate ESA liaison to the NASA Space Station Program Office. Similarly, NASA will provide and ESA will accommodate NASA liaison to the ESA Space Station Program Office. In addition, by mutual agreement, ESA may provide and NASA will accommodate ESA liaison to NASA Centers involved in the Space Station program, and NASA may provide and ESA will accommodate liaison to ESA Centers involved in the ESA Space Station program. Arrangements specifying all conditions relating to the liaison relationships will be agreed and co-signed by the Co-Chairmen of the PCC.

Article 8 - Management Aspects of the Space Station Program Primarily Related to Operations and Utilization

8.1. General

8.1.a. NASA and ESA each have responsibilities regarding the management of their respective operations and utilization activities and the overall Space Station operations and utilization activities, in accordance with the provisions of this MOU. NASA will have the responsibility for the overall planning for and direction of the operation of the manned base (including all elements within the operational Command and Control Zone (CCZ) of the manned base as defined in the program documentation provided for in Article 7) and the NASA-provided Polar Platform. ESA will have the responsiblity for the planning for and direction of the operation of the elements it provides which are separated from the manned base (specifically, the MTFF when outside the operational CCZ of the manned base and the ESA-provided Polar Platform when outside the operational CCZ of the STS, as defined in the program documentation provided for in Article 7). Operations and utilization activities will comprise long-range planning and top-level direction and coordination, which will be performed by the strategic-level organizations; detailed planning and support to the strategic-level organizations which will be performed by the tactical-level organizations; and implementation of these plans which will be performed by the execution-level organizations.

8.1.b. A Multilateral Coordination Board (MCB) will be established as soon as possible after the start of NASA's Phase C/D and will meet periodically over the lifetime of the program or promptly at the request of any partner with the task to ensure coordination of the activities of the partners related to the operation and utilization of the Space Station. The Parties to this MOU and the other partners will plan and coordinate activities affecting the safe, efficient and effective operation and utilization of the Space Station through the MCB, except as otherwise specifically provided in this MOU. The MCB will comprise the NASA Associate Administrator for Space Station; the ESA Director of Space Station and Platforms; the MOSST Deputy Secretary, Space Policy Sector; and the STA Director-General of the Research and Development Bureau. The NASA Associate Administrator for Space Station will chair the MCB. The Parties agree that all MCB decisions should be made by consensus. However, where consensus cannot be achieved on any specific issue within the purview of the MCB within the time required, the Chairman is authorized to take decisions. The Parties agree that, in order to protect the interests of all partners in the program, the operation and utilization of the Space Station will be most successful when consensus is reached and when the affected partners' interests are taken into account. MCB decisions will not modify rights of the partners specifically provided in this MOU. Decisions regarding the operation and utilization of the ESA-provided elements which are separated from the manned base and which do not have effects on the manned base associated with servicing at the manned base or have effects on the STS associated with servicing by the STS will be taken by ESA, except as otherwise specifically provided in Article 8.3.

8.1.c. The MCB will establish Panels which will be responsible for the long-range strategic coordination of the operation and utilization of the Space Station, to be called the System Operations Panel and the User Operations Panel respectively, described in detail below. The MCB will develop a charter that will define the organizational relationships and responsibilities of these Panels, and the organizational relationships of these Panels with the tactical- and execution-level organizations described below. Any modifications to the charter will be approved by the MCB. The MCB will approve, on an annual basis, a Consolidated Operations and Utilization Plan (COUP) for the Space Station based on the annual Composite Operations Plan and the annual Composite Utilization Plan developed by the Panels and described below. In doing so, the MCB will be responsible for resolving any conflicts between the Composite Operations Plan and the Composite Utilization Plan which cannot be resolved by the Panels. The COUP will be prepared by the User Operations Panel and agreed to by the System Operations Panel. The charter for these Panels will also delineate the Panels' delegated responsibilities with respect to adjustment of the COUP. The COUP will be implemented by the appropriate tactical- and execution-level organizations.

8.1.d. Manned Base Hardware. The following is provided to explain the relationships between the different types of elements on the manned base which are allocated for use by the partners.

The Space Station manned base includes:

- accommodations elements; and
- infrastructural elements.

The accommodations elements are the NASA-provided Laboratory Module, the ESA-provided APM, the STA-provided JEM including the Exposed Facility and the Experiment Logistics Modules, and the NASA-provided Attached Payload Accommodation Equipment. The infrastructural elements comprise all other manned base elements, including servicing elements and other elements that produce resources which permit all manned base elements to be operated and used.

8.1.d.1. Housekeeping. Both accommodations elements and infrastructural elements will be used for assembly, for verification and for maintenance of the manned base in an operational status, and also for the storage of element spares, crew provisions and safe haven capability, with secondary storage of crew provisions to be distributed equally among the three laboratories. In such use, they are referred to, respectively, as providing:

- housekeeping accommodations; and
- housekeeping resources.

During Phase C/D, these housekeeping accommodations and housekeeping resources will be controlled in appropriate program documentation as provided for in Article 7. During Phase E, these housekeeping accommodations and housekeeping resources will be controlled according to the mechanisms in Article 8.2.d.

8.1.d.2. Utilization. The accommodations and resources not required to maintain the manned base in an operational status will be used in connection with Space Station utilization, and are referred to, respectively, as:

- user accommodations; and
- utilization resources.

Details regarding the allocation of the Space Station user accommodations and utilization resources are provided in Article 8.3. NASA and ESA agree to seek to minimize the demands for housekeeping accommodations and housekeeping resources in order to maximize those available for utilization.

8.1.e. Platforms and MTFF. Because of the different character of the platforms and the MTFF, differentiation between accommodations and resources is not required. Mechanisms governing the operation of these elements are to be found in Article 8.2 and mechanisms governing the utilization of these elements are to be found in Article 8.3.

8.2. Operations

8.2.a. It is the goal of the Parties to this MOU to operate the Space Station in a manner that is safe, efficient and effective for both Space Station users and Space Station operators. To accomplish this, the MCB will establish, within three months of its establishment, a System Operations Panel (SOP) to coordinate strategic-level operations activities and operations planning activities as provided for in Article 8.1.c.

8.2.b. The SOP will comprise one member each from NASA, ESA and the other partners. Members may send designated alternates to SOP meetings. In addition, each partner may call upon relevant expertise as necessary to support SOP activities. The SOP will take decisions by consensus; in the event of failure to reach consensus on any issue, the issue will be forwarded to the MCB for resolution. In the interest of efficient management, NASA and ESA recognize that the SOP should take the responsibility routinely to resolve all operations issues as expeditiously as possible rather than refer such issues to the MCB.

8.2.c. The SOP will develop, approve and maintain an Operations Management Plan for the operation, maintenance and refurbishment of and logistics for the manned base, the NASA-provided Polar Platform and the ESA-provided Polar Platform insofar as these platforms have effects on the STS associated with their servicing by the STS, and the MTFF insofar as it as effects on the manned base associated with its servicing at the manned base during Phase E. This Plan will describe relationships among the strategic, tactical and execution levels of operations management, where the strategic level is coordinated by the SOP; the tactical level, by the tactical operations organization referred to in Article 8.2.e; and the execution level, by implementing organizations and field centers. Consistent with the other provisions of this Article, the Operations Management Plan will also address operational requirements for the manned base, the NASA-provided Polar Platform and the ESA-provided Polar Platform insofar as these platforms have effects on the STS associated with their servicing by the STS, the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base and Space Station-unique ground elements. The Operations Management Plan will provide the procedures for preparation of the baseline operations plans and maintenance plans provided for in Articles 6.1.a.24 and 6.2.a.27, annual refinements to these baseline plans, and the Composite Operations Plan described in Article 8.2.d, including procedures for adjustment of these plans as further information becomes available.

8.2.d. On an annual basis, NASA and ESA will each provide to the SOP any significant refinements to their baseline operations plans and maintenance plans five years in advance. Using the operations and maintenance plans and these refinements provided by all of the partners, including requirements for use of Space Station-unique ground elements, the SOP will develop and approve an annual Space Station Composite Operations Plan (COP) consistent with the annual Space Station Composite Utilization Plan described in Article 8.3.f. The COP will also identify the housekeeping accommodations and housekeeping resources required for maintenance of the manned base in an operational status. Compatibility of the COP and the Composite Utilization Plan must be assured through coordination between the SOP and the User Operations Panel, described in Article 8.3.d, during the preparation and approval process.

8.2.e. NASA, with the participation of all the partners, will be responsible for integrated tactical-level activities for Space Station manned base operations. To this end, NASA will establish an integrated tactical operations organization and the other partners will participate in discharging the responsibilities of this organization. ESA and the other partners will provide personnel to the integrated tactical operations organization who will bring expertise on the elements each provides and will participate in overall integrated tactical operations activities. NASA and ESA will consult and agree regarding the responsibilities to be discharged by the ESA personnel. NASA and ESA will also consult and agree regarding the number of ESA personnel and all administrative conditions related to these personnel. In conjunction with the integrated activities, NASA, ESA and the other partners will each perform distributed tactical-level activities related to the elements each provides, such as decentralized system operations support planning, user support planning, logistics planning, and the accommodations assessments described in Article 8.3.h. Tactical-level activities will include planning for system operations and for user support activities across all manned base elements. Tactical-level activities for elements separated from the manned base when outside the operational CCZ of the STS or the manned base, as defined in the program documentation provided for in Article 7, will be performed by the element provider. However, where the same services, such as transportation, logistics and communications, are required by both the manned base and elements which are operating separated from the manned base, planning for these services will be performed by the integrated tactical operations organization.

8.2.f. Tactical Operations Plans (TOP's) for the manned base and for the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base will be developed by the tactical operations organization described in Article 8.2.e to implement the COUP. Each TOP will include Increment Plans (IP's) for a period of two years prior to launch of the STS to the manned base for a specific increment. (An increment is normally the interval between visits of the STS for the purpose of resupply in support of manned base operations and utilization as approved in the COUP.) Each IP will describe the detailed manifest of user payloads, systems support equipment and supplies needed to support the increment. Each IP will also describe changes to the complement of hardware and software to be flown during that increment and the payload and system support activities needed to carry out the activities approved in the COUP for that increment. The IP will identify the crew complement and define logistics requirements including STS interface requirements, changes to housekeeping resource requirements, changes to housekeeping accommodation requirements and communication requirements, including TDRSS use and requirements for distribution of data, to support the subject increment.

8.2.g. NASA, with the participation of all the partners, will be responsible for integrated execution-level planning for and execution of the day-to-day operation of the manned base. ESA and the other partners will participate in discharging the responsibilities of the Space Station Control Center (SSCC), established and managed by NASA, which will conduct execution-level activities and support tactical planning. ESA and the other partners will provide personnel to the SSCC. These personnel will bring expertise on the elements that partner provides, will participate in overall SSCC-based activities, and will support real-time on-orbit activities with emphasis on the elements each provides. NASA and ESA will consult and agree regarding the responsibilities to be discharged by the ESA personnel. NASA and ESA will also consult and agree regarding the number of ESA personnel and all administrative conditions related to these personnel. In conjunction with the integrated activities, NASA, ESA and the other partners will each perform distributed execution-level activities related to the elements each provides, such as monitoring and support of real-time systems operations. NASA, ESA and the other partners will provide engineering support centers to perform detailed engineering assessments and real-time operations support to the SSCC required for the operational control of the manned base elements they provide. Execution-level activities for elements separated from the manned base when outside the operational CCZ of the STS or the manned base, as defined in the program documentation provided for in Article 7, will be the responsibility of the element provider. The partners may also participate in and provide personnel to other execution-level activities at other sites as agreed.

8.2.h. The International Operational Concepts Working Group (IOCWG), established by the Space Station Phase B MOU's, will continue to advise the Parties to this MOU in planning for the establishment of the SOP. Once the SOP is established, the activities of the IOCWG will end.

8.3. Utilization

8.3.a. Manned Base

8.3.a.1. NASA and MOSST will provide Space Station manned base infrastructural elements to assemble, maintain, operate and service the manned base; NASA and MOSST will also provide resources derived from these infrastructural elements to the other partners as provided in Article 8.3.a.2. ESA will retain the use of 51% of the user accommodations on its APM; NASA will retain the use of 97% of the user accommodations on its accommodations elements; NASA and ESA will each provide MOSST 3% of the user accommodations on their accommodations elements; and ESA will provide NASA the remaining user accommodations on its APM. NASA, ESA and MOSST will each control the selection of users for their allocations of user accommodations; such NASA, ESA and MOSST control of the selection of users for their allocation of user accommodations will be exercised in accordance with the procedures in this MOU and in the NASA-MOSST MOU for developing the Composite Utilization Plan.

8.3.a.2. Allocation of manned base resources among the partners will be in accordance with the following approach. Housekeeping resources required by all elements, and provided as noted in Article 8.1.d.1, will be set aside. The utilization resources will be allocated as follows: 20% of utilization resources will be allocated to NASA because of its Attached Payload Accommodation Equipment; 3% of utilization resources will be allocated to MOSST; the remaining utilization resources will be apportioned equally among the three laboratory modules. ESA will be allocated 50% of the utilization resources apportioned to the ESA-provided APM and STA will be allocated 50% of the utilization resources apportioned to the STA-provided JEM. NASA will be allocated 100% of the utilization resources apportioned to the NASA-provided Laboratory Module, the remaining 50% of the utilization resources apportioned to the ESA-provided APM and the remaining 50% of the utilization resources apportioned to the STA-provided JEM. The above allocation of utilization resources is to the partner, not to the elements, and may be used by the partner on any Space Station element consistent with the COP and the Composite Utilization Plan. More than this allocation of any utilization resource may be gained by each partner through barter or purchase from other partners.

8.3.a.3. ESA's allocation of user accommodations and utilization resources will begin once the APM is verified following assembly to the manned base.

8.3.a.4. Manned base utilization resources are power, user servicing capacity, heat rejection capacity, data handling capacity, total crew time and EVA capacity. The initial list of manned base utilization resources to be allocated is power, user servicing capacity and total crew time. All other manned base utilization resources may be used without allocation. To support the operation and full international utilization of the Space Station manned base as defined in Article 3, NASA plans to provide the number of STS flights per year baselined by the SSCB during Phase C/D. From the total Space Station user payload capacity available on STS flights actually flown to and from the manned base each year, each partner will have the right to purchase STS launch and return services for its Space Station utilization activities, up to its allocated percentage of utilization resources. (The foregoing does not apply to STS launch and return capacity provided to and from the manned base in connection with Space Station evolutionary additions.) Similarly, the partners will have the right to purchase, up to their allocated percentage of utilization resources, TDRSS data transmission capacity available to the manned base. The User Operations Panel, defined in Article 8.3.d, will update the lists of utilization resources and allocated utilization resources as necessary as NASA and the other partners gain experience.

8.3.b. Platforms

8.3.b.1. In recognition of the fact that platforms are separate elements that do not require extensive support from the infrastructural elements of the manned base, platforms are treated separately from the manned base.

8.3.b.2. NASA and ESA will share the use of each other's polar platforms on a balanced reciprocal basis, recognizing that the two platforms may have different capabilities and that the user community may propose specific splits based on actual payloads; such proposals must be agreed to by NASA and ESA, and by MOSST with respect to its 3% utilization of the polar platforms provided for in Article 8.3.b.3, and processed by the User Operations Panel as part of the development of the Composite Utilization Plan provided in Article 8.3.f.2. NASA and ESA will also provide associated user integration and user operations support to each other and each other's users.

8.3.b.3. MOSST will be provided 3% utilization of both the NASA and ESA polar platforms together with the associated user integration and user operations support. STA may purchase, barter or enter into other arrangements for platform utilization.

8.3.c. Man-Tended Free Flyer

8.3.c.1. ESA will retain the total use of the MTFF it provides.

8.3.c.2. Notwithstanding Article 8.3.c.1, each year, NASA will have an option to use up to 25% of MTFF utilization capacity by purchase at prices ESA routinely charges comparable customers or by barter such as for an amount of utilization resources and/or user accommodations. The conditions of such purchase or barter will be agreed between NASA and ESA.

8.3.c.3. In case of total use of the MTFF by ESA, all accommodations and resources required to service the MTFF at the manned base will come out of the user accommodations and utilization resources available to ESA as provided in Article 8.3.a.

8.3.d. It is the goal of the Parties to use the Space Station in a safe, efficient and effective manner. To accomplish this, the MCB will establish, within three months of its establishment, a User Operations Panel (UOP), to assure the compatibility of utilization activities of the manned base, the polar platforms, and use by the MTFF of manned base utilization resources and user accommodations. The UOP will comprise one member each from NASA, ESA and the other partners. Members may send designated alternates to UOP meetings. In addition, each partner may call upon relevant expertise as necessary to support

UOP activities. The UOP will take decisions by consensus; except as noted in Article 8.3.f.2, in the event of failure to reach consensus on any issue, the issue will be forwarded to the MCB for resolution. In the interest of efficient management, NASA and ESA recognize that the UOP should take the responsibility to routinely resolve all utilization issues as expeditiously as possible rather than refer such issues to the MCB.

8.3.e. The UOP will develop, approve and maintain a Utilization Management Plan which will describe relationships among the strategic, tactical and execution levels of utilization management, where the strategic level is coordinated by the UOP; the tactical level, by the integrated tactical operations organization described in Article 8.2.e; and the execution level, by implementing organizations and field centers. The Plan will also establish processes for utilization of the Space Station elements, including the user support centers and other Space Station-unique ground elements provided by all the partners, consistent with Article 8.3.d; define standard user integration and user operations support; and describe the approach to distributed user integration and operations. The Plan will provide procedures for preparation of the partners' Utilization Plans and Composite Utilization Plan described in Article 8.3.f, including procedures for adjustment of these Plans as further information becomes available.

8.3.f. Utilization Plan for the Manned Base and the Polar Platforms

8.3.f.1. On an annual basis, five years in advance, NASA and ESA each will develop a Utilization Plan for all proposed uses of its allocation of manned base user accommodations and utilization resources, for all proposed uses of unallocated manned base utilization resources and Space Station-unique ground elements, and for all uses of the polar platforms. Each partner will satisfy the requirements of its users for storage within the user accommodations available to that partner, with the exception of temporary on-orbit storage in the Integrated Logistics System carriers in which user equipment, including MTFF equipment, is launched or returned to Earth as specified in the applicable Increment Plan. As regards the MTFF, the ESA Utilization Plan will include all uses of manned base user accommodations and utilization resources required to service the MTFF at the manned base, information necessary to determine whether any planned utilization of the MTFF would have effects on the manned base associated with its servicing at the manned base, and information related to Article 9.8(a) of the Intergovernmental Agreement. NASA and ESA each will prioritize and propose appropriate schedules for the user activities in its Utilization Plan, including the use of user support centers and other Space Station-unique ground elements to support the utilization of the flight elements. These individual Utilization Plans will take into consideration all factors necessary to assure successful implementation of the user activities, including any relevant information regarding crew skills and special requirements associated with the proposed payloads.

8.3.f.2. NASA and ESA each will forward its Utilization Plan to the UOP. Using the Utilization Plans of NASA, ESA and the other partners, the UOP will develop the Composite Utilization Plan (CUP), covering the use of both flight and Space Station-unique ground elements, based on all relevant factors, including each element-provider's recommendations regarding resolution of technical and operational incompatibilities among the users proposed for its elements. In its use of the Space Station, each partner will seek, through the mechanisms established in this MOU, to avoid causing serious adverse effects on the use of the Space Station by the other partners. In the event of failure of the UOP to reach consensus on the utilization of the manned base and/or related Space Station-unique ground elements, the issue will be forwarded to the MCB for resolution. In the event of failure of the UOP to reach consensus on the utilization of the ESA-provided Polar Platform, ESA will take the decision, and in the event of failure of the UOP to reach consensus on the utilization of the NASA-provided Polar Platform, NASA will take the decision; however, in either event, NASA and ESA will respect the utilization rights of Canada and of each other in any such decisions.

8.3.f.3. Utilization Plans proposed by NASA, ESA and the other partners which fall completely within their respective allocations and do not conflict operationally or technically with one another's Utilization Plans will be automatically approved. However, Articles 9.8(a), 9.8(b) and 9.11 of the Intergovernmental Agreement will apply.

8.3.g. Utilization Plan for the MTFF

8.3.g.1. The MTFF Utilization Plan will be developed and approved by ESA. As appropriate, MTFF utilization will be consistent with Articles 8.3.c.2 and 8.3.f.1.

8.3.h. Each partner will participate in integrated tactical-level planning of user activities. To this end, each partner will provide personnel to the operations organization described in Article 8.2.e. These personnel will participate in integrated tactical-level planning of user activities; they will also support the strategic-level planning of user activities. NASA and ESA will consult and agree regarding the responsibilities to be discharged by the ESA personnel. NASA and ESA will also consult and agree regarding the number of ESA personnel and all administrative conditions related to these personnel. In addition, partners providing user accommodations will be responsible for providing standard user integration and user operations support to users of other partners or other partners as users, including conducting assessments of the flow of payload integration activities for all payloads manifested in the user accommodations they provide. Accommodation assessments for individual payloads manifested in a laboratory module covering engineering, operations and software compatibility will also be performed by the partner providing that laboratory module in support of the preparation and execution of Tactical Operations Plans and Increment Plans. Similarly, MOSST will be responsible for providing standard user integration and user operations support for users of the other partners or other partners as users of the flight elements provided by MOSST; and NASA will be responsible for providing standard user integration and user operations support for users of the other partners or other partners as users of the manned base systems/subsystems provided by NASA.

8.3.i. Each partner will participate in discharging the responsibilities of the Payload Operations Integration Center (POIC) established and managed by NASA which will be responsible for assistance to manned base users in planning and executing user activities on the manned base, for overall direction of the execution of user activities on the manned base, and for interaction with the SSCC in order to coordinate user activities with systems operations activities. Each partner will provide personnel to the POIC. NASA and ESA will consult and agree regarding the responsibilities to be discharged by the ESA personnel. NASA and ESA will also consult and agree regarding the number of ESA personnel and all administrative conditions related to these personnel. The interaction between the POIC and SSCC will be described in the Operations Management Plan. Both NASA and ESA will provide user support centers which will function within the framework of NASA's responsibilities for the POIC. The interactions between the user support centers and the POIC will be described in the Utilization Management Plan. NASA and ESA will each be responsible, relative to the elements they provide which are separated from the manned base, for assistance to users in planning and executing user activities, for direction of the execution of user activities and for interaction with the MTFF and polar platform control centers to coordinate user and element operations activities.

8.3.j. In working out problems which may arise after the development of the COUP, in the case of a technical or operational incompatibility between users, the partner(s) providing the element(s) in which the users have accommodations, as well as other impacted partners, will provide appropriate analyses and recommendations to the appropriate strategic-, tactical- or execution- level organization for resolution of conflicts. However, if such conflict only has impacts within a single manned base element and only impacts users of the provider of that element, the partner providing that manned base element will be responsible for resolving such conflicts in accordance with the content of the COUP; conflicts related to proposed polar platform utilization will be resolved as provided in Article 8.3.f.2.

8.3.k. NASA, ESA and the other partners may at any time barter for, sell to one another or enter into other arrangements for any portion of their Space Station allocations, and are free to market the use of their allocations individually or collectively, according to the procedures established in the Utilization Management Plan. The terms and conditions of any barter or sale will be determined on a case-by-case basis by the parties to the transaction. The partner providing allocations will ensure that the obligations it has undertaken under this MOU are met. NASA, ESA and the other partners each may retain the revenues they derive from such marketing.

8.3.1. NASA and ESA will make their Space Station-unique ground elements, including user support centers, available for use by each other and the other partners in order to support fully both the standard and special user integration and operations support approved in the CUP and the requirements in the COP. Any special user integration or user operations support provided by a partner to users of the other partners or other partners as users will be provided on a reimbursable basis at prices routinely charged comparable users for similar services.

8.3.m. The International Utilization Coordination Working Group (IUCWG), established by the Space Station Phase B MOU's, will continue to advise the Parties to this MOU in planning for the establishment of the UOP. Once the UOP is established, the activities of the IUCWG will end.

8.4. In order to protect the intellectual property of Space Station users, procedures covering all personnel, including Space Station crew, who have access to data will be developed by the MCB.

8.5. The partners will seek to outfit the NASA-provided Laboratory Module, the ESA-provided APM and the STA-provided JEM to equivalent levels by the end of Space Station assembly in Phase C/D.

Article 9 - Operations Costs Responsibilities

9.1. The Parties will seek to minimize operations costs for the Space Station. The Parties will also seek to minimize the exchange of funds, for example, through the performance of specific operations activities.

9.1.a. The costs associated with ESA's providing personnel to undertake integrated tactical- and execution-level activities as provided for in Articles 8.2.e, 8.2.g, 8.3.h, and 8.3.i will be agreed between NASA and ESA and will be a contribution towards the satisfaction of ESA's common system operations costs responsibilities established below.

9.2. Element operations costs

9.2.a. NASA and ESA will each have operational responsibilities for the elements it provides as detailed in Article 8. Such operational responsibilities mean that NASA and ESA will each be financially responsible for element operations costs, that is, costs attributed to operating and to sustaining the functional performance of the flight elements that it provides, such as ground-based maintenance, sustaining engineering, provision of spares, launch and return costs for spares, launch and return costs of the fraction of the Integrated Logistics System carriers provided for in Article 3.2 that is attributable to spares, and also costs attributed to the maintenance and operation of element-unique ground centers.

9.3. Common system operations costs

9.3.a. Manned Base. Other than the element operations costs covered in Article 9.2.a, NASA, ESA and the other partners will equitably share the common system operations costs; that is, the costs attributed to the operation of the manned base as a whole. The categories comprising common system operations costs are: integrated tactical planning activities performed by the integrated tactical operations organization provided for in Article 8.2.e, including user integration planning and maintenance of common documentation; space systems operations (SSCC-based operations, SSCC maintenance and common elements of the Software Support Environment); POIC-based operations and POIC maintenance; Integrated Logistics System operations, including consumables and common inventory management activities; prelaunch/postlanding processing of logistics carriers; launch to orbit and return of consumables, crew and crew logistics, and launch and return of the fraction of the Integrated Logistics System carriers provided for in Article 3.2 that is attributable to consumables and crew logistics; and transmission of housekeeping data between the manned base and the ground (SSCC, POIC and launch and landing sites). Each partner will be responsible for a percentage of common system operations costs equal to the percentage of Space Station utilization resources allocated to it in Article 8.3.a.2. ESA's responsibility for sharing common system operations costs will begin following the assembly and verification of the APM.

9.3.b. Platforms. NASA and ESA will each be responsible for the common system operations costs for the platforms which they provide.

9.3.c. Man-Tended Free Flyer. ESA will be responsible for the common system operations costs for the MTFF it provides.

9.3.d. Any changes to the list of common system operations costs in this Article will be made by agreement among the partners.

9.4. The Parties to this MOU and the other partners will work through the SOP to identify the detailed contents to be included in each common system operations cost category. The partners will also, each year, report to the SOP on their forecasts for future years for all costs included in the common system operations costs of the manned base and on their identified actual annual common system operations costs. The SOP will develop detailed procedures for implementing this Article. If possible, after the partners have gained experience in the operation of the Space Station, the SOP will endeavor to establish a fixed value for the annual common system operations costs.

9.5. Costs of user activities such as payload/experiment design, development, test and evaluation (DDT&E); payload ground processing; provision of payload/experiment spares and associated equipment; launch and return of payloads/experiments, spares and associated equipment; launch and return of the fraction of the Integrated Logistics System carriers provided for in Article 3.2 that is attributable to user payloads/ experiments, spares and associated equipment; and any special user integration or user operations support, including specialized crew training, will be the responsibility of Space Station users of the partners or of individual partners as users. Such costs will not be shared among NASA, ESA and the other partners, nor will such costs contribute toward the satisfaction of common system operations costs responsibilities. In addition, the DDT&E and operations costs of the users' support centers will not be shared among NASA, ESA and the other partners.

9.6. NASA, ESA and the other partners will not recoup their DDT&E costs for their elements from one another in the operation and utilization of the Space Station.

9.7. In case of failure of any partner to perform its operations responsiblities or to provide for its share of common system operations costs, the partners will meet to discuss what action should be taken. Such action could result in, for example, an appropriate reduction of the failing partner's rights to its allocations.

Article 10 - Safety

10.1. In order to assure safety, NASA has the responsibility, working with the other partners, to establish overall Space Station safety requirements and plans covering Phase C/D and Phase E. Such requirements and plans for Phase C/D have been established, and development of further safety requirements and plans for Phase C/D and Phase E and changes to safety requirements and plans will be processed, according to the procedures in Articles 7 and 8. As far as the elements separated from the manned base and their payloads are concerned, NASA has the responsiblity to establish and implement overall safety requirements and plans governing the NASA-provided Polar Platform, and ESA has the responsiblity to establish and implement overall safety requirements and plans governing the ESA-provided Polar Platform and the MTFF. The overall Space Station safety requirements and plans will be applicable to the MTFF insofar as it has effects on the manned base associated with its servicing at the manned base. STS safety requirements will be applicable to the ESA-provided Polar Platform insofar as it has effects on the STS associated with its servicing by the STS.

10.2. Each partner will develop detailed safety requirements and plans, using its own standards where practicable, for its manned base hardware and software that meet or exceed the overall Space Station safety requirements and plans. Each partner will have the responsibility to implement applicable overall and detailed Space Station safety requirements and plans throughout the lifetime of the program, and to certify that such safety requirements and plans have been met with respect to the Space Station manned base elements and payloads it provides. ESA will have the responsibility to certify that the MTFF and ESA-provided Polar Platform and their payloads are safe. However, NASA will have the overall responsiblity to certify that all Space Station manned base elements and payloads are safe, including the MTFF and its payloads insofar as they have effects on the manned base associated with their servicing at the manned base. NASA will also have the responsibility to certify that the ESA-provided Polar Platform and its payloads are safe insofar as they have effects on the STS associated with their servicing by the STS.

10.3. NASA will conduct system safety reviews which ESA will support. NASA, ESA and the other partners will also conduct safety reviews of the elements and payloads they provide; NASA will participate in and support such reviews by the other partners. MOSST will also participate in and support safety reviews by the other partners as appropriate related to the MOSST-provided elements and MOSST payloads. NASA and MOSST support to such safety reviews will include provision of necessary safety-related information to enable the other partners to conduct their reviews. Furthermore, status reports on safety requirements and plans will be a standard agenda item at the Program Management Reviews provided for in Article 7.1.i. The partners will participate as appropriate in any Space Station safety review boards established by NASA.

10.4. NASA will have the responsibility for taking any decision necessary to protect the safety of the manned base, including all elements operating in conjunction with the manned base, or its crew in an emergency.

Article 11 - Space Station Crew

11.1. ESA has the right to provide personnel to serve as Space Station crew from the time that ESA begins to share common system operations costs as provided in Article 9.3.a. NASA will provide flight opportunities for ESA Space Station crew satisfying the percentage of the total crew requirement equal to the percentage of manned base utilization resources allocated to ESA in Article 8.3.a.2. Flight of ESA Space Station crew will be satisfied over time, not necessarily on each specific crew rotation cycle. The SOP will review the implementation of this paragraph on a biennial basis.

11.2. During assembly and verification, a fully trained ESA crew member will participate in the on-orbit assembly and system verification of the ESA-provided APM and other assigned flight element assembly and system verification tasks planned during that on-orbit period as provided in the verification plan described in Articles 6.1.a.4. and 6.2.a.3. Further, during the first two servicings of the MTFF at the manned base, a fully trained ESA crew member will participate in the relevant activities.

11.3. Space Station crew will meet medical standards and security and suitability requirements developed by NASA in consultation with ESA and the other partners regarding Space Station crew qualifications for long-term manned space flight. NASA and ESA will jointly certify that these standards and requirements have been met by the ESA Space Station crew. Furthermore, the MCB may establish additional criteria for Space Station crew. Following certification, all Space Station crew will enter into an appropriate training cycle in order to acquire the skills necessary to conduct Space Station operations and utilization. Such training will be conducted in groups, subject to the requirements of different functional specializations. The training will include integrated manned systems operations training conducted primarily at NASA centers and element-specific operations training conducted primarily by the partner providing the element at appropriate centers of all of the partners. In full consultation with ESA regarding the flight assignments of ESA crew members, NASA will designate, from among the certified Space Station crew, specific crew complements, which include the Space Station Commander, for specific crew rotation cycles, consistent with Article 11.1. NASA will designate specific crew complements to support payload requirements identified in the COUP. A specific crew complement will be trained as a team in preparation for a specific crew rotation cycle, subject to requirements of different functional specializations.

11.4. NASA and ESA will be financially responsible for all compensation, medical expenses, subsistence costs on Earth, and training for Space Station crew which they provide. Full training for all assigned duties will be required.

11.5. The Code of Conduct for the Space Station will be developed by NASA, with the full involvement of ESA, MOSST and the GOJ, and approved for the Space Station program in accordance with the principles for reaching decisions established in Article 8.1.b. It will, inter alia: establish a clear chain of command; set forth standards for work and activities in space, and, as appropriate, on the ground; establish responsibilities with respect to elements and equipment; set forth disciplinary regulations; establish physical and information security guidelines; and provide the Space Station Commander appropriate authority and responsibility, on behalf of all the partners, to enforce safety procedures and physical and information security procedures in or on the Space Station.

11.6. ESA crew selected for operating the MTFF outside the operational CCZ of the manned base are not considered Space Station crew, pursuant to this Article, for the purposes of that activity.

Article 12 - Transportation, Communications and Other Non-Space Station Facilities

12.1. Transportation

12.1.a. For purposes of design of Space Station elements and payloads, NASA's STS is the baseline launch and return transportation system for the Space Station manned base and for the NASA-provided Polar Platform. ESA's Space Transportation System is the baseline launch transportation system for the MTFF and the ESA-provided Polar Platform.

12.1.b. NASA will provide reimbursable STS launch services to ESA in connection with the assembly of the ESA-provided APM to the manned base and its initial outfitting in accordance with the program documentation described in Article 7.1. NASA will also provide reimbursable launch and return services in connection with the logistics requirements of manned base elements. NASA will also provide reimbursable launch and return services in connection with the MTFF when it is serviced at the manned base and in connection with manned base users; availability of STS services for such purposes is as provided in Articles 8.3.a.4 and 8.3.c. NASA will also provide reimbursable launch services in connection with servicing of the ESA-provided Polar Platform, with details to be agreed by NASA and ESA, if appropriate STS capability exists and if ESA selects to use this capability. Reimbursement for such launch services may be in cash or agreed kind. All reimbursable STS services will be provided under launch services agreements. NASA will also provide launch and return services in connection with manned base common system operations logistics; costs for such services will be shared among the partners as provided in Article 9.3. ESA will provide the initial launch of the MTFF and the ESA-provided Polar Platform. ESA will also provide launch and return services in connection with the logistics requirements of the MTFF when it is not serviced at the manned base.

12.1.c. Other government or private sector space transportation systems of partners may be used in connection with the Space Station if they are compatible with the Space Station. Specifically, ESA will have the right of access to the Space Station manned base using the ESA Space Transportation System, including Ariane and Hermes. Recognizing that the responsibility for developing these systems and for making them technically and operationally compatible with the manned base rests with ESA, NASA will provide to ESA that information necessary for ESA to make them compatible. Technical, operational and safety requirements for access to the manned base will be controlled in appropriate program documentation as provided for in Articles 7 and 8.

12.1.d. With respect to financial conditions, NASA and ESA will provide reimbursable launch and return services to each other, to the other partners and to each other's and the other partners' users at prices they routinely charge comparable users. Launch and return services related to manned base common system operations logistics will also be made available by NASA on the same basis.

12.1.e. Both NASA and ESA will use their best efforts to accommodate additional launch and return requirements in relation to the Space Station, as well as proposed requirements and flight schedules related to the Space Station activities described above.

12.1.f. Each partner will respect the proprietary rights in and confidentiality of appropriately marked data and goods to be transported on its space transportation system.

12.2. Communications

12.2.a. Space Station communications will involve space-to-ground, ground-to-space, ground-to-ground and space-to-space data transmission. The TDRSS space network is the baseline communication system for the manned base elements and payloads, as well as for the NASA-provided Polar Platform and its payloads. ESA's Data Relay Satellite system (EDRS) is the baseline communication system for the ESA-provided Polar Platform and the MTFF and their payloads. ESA will be responsible for ensuring communications compatibility of the MTFF with the manned base for proximity operations, docking and servicing and of the ESA-provided Polar Platform with the STS for servicing as applicable. On a reimbursable basis, NASA and ESA will use their best efforts to accommodate, with their respective communication systems, specific Space Station-related requirements of each other and the other partners. With respect to financial conditions, NASA and ESA will provide such communication services at prices no higher than those they routinely charge comparable customers. Other communication systems may be used on the manned base by ESA, the other partners or Space Station users if such communication systems are compatible with the manned base and manned base use of TDRSS. Technical and operational requirements related to Space Station communications will be controlled in appropriate program documentation as provided for in Articles 7 and 8.

12.2.b. NASA and ESA will consult regarding the possible future addition of manned base capability to accommodate ESA-provided facilities permitting manned base use of EDRS, if compatible with the manned base and with manned base use of TDRSS.

12.2.c. Unless otherwise agreed by NASA and ESA, ground-to-ground transmission of polar platform data from one partner to the other partners or the other partners' users will conform to the communications transportation formats, protocols and standards agreed to by the Consultative Committee for Space Data Systems (CCSDS).

12.2.d. Partners and users of the partners may implement measures to ensure confidentiality of their utilization data passing through the Space Station Information System and other communication systems being used in connection with the Space Station. (Notwithstanding the foregoing, data which are necessary to assure safe operations will be made available according to procedures in the Utilization Management Plan and their use will be restricted to safety purposes only.) Each partner will respect the proprietary rights in, and the confidentiality of, the utilization data passing through its communication systems, including its ground network and the communication systems of its contractors, when providing communication services to another partner.

12.3. Other Non-Space Station Facilities

12.3.a. Should ESA desire to use the Space Shuttle, Spacelab, or other NASA facilities on a cooperative or reimbursable basis to support the development of its Space Station Utilization Plan or to support its Space Station detailed design or development activities, NASA will use its best efforts to accommodate ESA's proposed requirements and schedules. Likewise, should NASA desire to use Ariane, Hermes or other ESA facilities on a cooperative or reimbursable basis to support the development of its Space Station Utilization Plan or to support its Space Station detailed design or development activities, ESA will use its best efforts to accommodate NASA's proposed requirements and schedules.

12.3.b. If NASA and ESA agree that it is appropriate and necessary for the conduct of the cooperative program, NASA and ESA will use their good offices in connection with attempting to arrange for the use of U.S. and European Governments' or contractors' facilities by the Parties and/or their contractors. Such use will be subject to separate arrangements between the user and the owner of the facilities.

Article 13 - Advanced Development Program

13.1. NASA and ESA each are conducting Space Station advanced development programs in support of their respective detailed design and development activities. Cooperation in such advanced development activities will be considered on a case-by-case basis and entered into where it is advantageous to both sides and where there are reciprocal opportunities.

13.2. ESA proposals to use NASA advanced development test beds or other NASA facilities in support of ESA's Space Station advanced development program will be considered on a case-by-case basis either on a cooperative or reimbursable basis. Likewise, NASA proposals to use ESA's facilities in support of NASA's Space Station advanced development program will be considered on a case-by-case basis either on a cooperative or reimbursable basis.

13.3. Should ESA desire to use the Space Shuttle or Spacelab on a cooperative or reimbursable basis to support ESA Space Station advanced development activities, NASA will use its best efforts to accommodate ESA's proposed requirements and flight schedules. Likewise, should NASA desire to use ESA launch vehicles on a cooperative or reimbursable basis to support NASA Space Station advanced development activities, ESA will use its best efforts to accommodate NASA's proposed requirements and flight schedules.

Article 14 - Space Station Evolution

14.1. The partners intend that the Space Station will evolve through the addition of capability and will strive to maximize the likelihood that such evolution will be effected through contributions from all the partners. To this end, it will be the object of the Parties to provide, where appropriate, the opportunity to the other partners to cooperate in their respective proposals for additions of evolutionary capability. The Space Station together with its additions of evolutionary capability will remain a civil station, and its operation and utilization will be for peaceful purposes, in accordance with international law.

14.2. This MOU sets forth rights and obligations concerning only the elements listed in Article 3, except that this Article and Article 16 of the Intergovernmental Agreement will apply to any additions of evolutionary capability. As such, this MOU does not commit either Party to participate in, or grant either Party rights in, the addition of evolutionary capability.

14.3. NASA and ESA agree to study evolution concepts for the Space Station during Phase C/D and Phase E. NASA will be responsible for development of overall manned base evolution concepts, in consultation with ESA and the other partners, and for integrating ESA's and the other partners' evolution concepts into an overall manned base evolution plan. ESA will be responsible for development and decision on subsequent implementation of evolution concepts for the ESA-provided Polar Platform and for the MTFF insofar as they have no technical or operational impacts on the STS or the manned base, in accordance with Articles 14.6 and 14.7.

14.4. NASA, ESA, and the other partners will participate in an International Evolution Working Group (IEWG) to coordinate their respective evolution studies and to consider overall Space Station evolution concepts and planning activities.

14.5. The MCB will review specific evolutionary capabilities proposed by any partner, assess the impacts of those plans on the other partners' elements and on the manned base, and review recommendations for minimizing potential impacts on Space Station activity during the addition of evolutionary capabilities.

14.6. Following the review and assessment provided for in Article 14.5, and consistent with the provisions of the Intergovernmental Agreement, cooperation between or among partners regarding the sharing of addition(s) of evolutionary capability will require either amendment of the relevant NASA-ESA, NASA-GOJ and NASA-MOSST MOU's or a separate agreement to which, to the extent that such addition is on the manned base or has a technical or operational impact on the STS or the manned base, NASA is a party to ensure that such addition is consistent with NASA's overall programmatic responsibilities as detailed in this MOU.

14.7. Following the review and assessment provided for in Article 14.5, and consistent with the provisions of the Intergovernmental Agreement, the addition of evolutionary capability by one partner will require prior notification of the other partners, and, to the extent that such addition is on the manned base or has a technical or operational impact on the STS or the manned base, an agreement with NASA to ensure that such addition is consistent with NASA's overall programmatic responsibilities as detailed in this MOU.

14.8. The addition of evolutionary capability will in no event alter the rights and obligations of either Party to this MOU concerning the elements listed in Article 3, unless otherwise agreed by the affected Party.

Article 15 - Cross-Waiver of Liability; Exchange of Data and Goods; Treatment of Data and Goods in Transit; Customs and Immigration; Intellectual Property; Criminal Jurisdiction

The Parties note that, with respect to the cross-waiver of liability, exchange of data and goods, treatment of data and goods in transit, customs and immigration, intellectual property and criminal jurisdiction, the relevant provisions of the Intergovernmental Agreement apply.

Article 16 - Financial Arrangements

16.1. Each Party will bear the costs of fulfilling its responsibilities, including but not limited to costs of compensation, travel and subsistence of its own personnel and transportation of all equipment and other items for which it is responsible under this MOU. However, as provided in Article 9.3, the partners will equitably share common system operations costs.

16.2. The ability of each Party to carry out its obligations is subject to its funding procedures and the availability of appropriated funds.

16.3. In the event that funding problems are arising that may affect a partner's ability to fulfill its responsibilities under this MOU, that partner will promptly notify and consult with the other partners. Further, the Parties undertake to grant high priority to their Space Station programs in developing their budgetary plans.

16.4. The Parties will seek to minimize the exchange of funds while carrying out their respective responsibilities in this cooperative program, including, if they agree, through the use of barter, that is, the provision of goods or services.

Article 17 - Public Information

17.1. NASA and ESA will be responsible for the development of an agreed Public Affairs Plan that will specify guidelines for NASA/ESA cooperative public affairs activities during the detailed design, development, operation and utilization of the Space Station.

17.2. Within the Public Affairs Plan guidelines, both NASA and ESA will retain the right to release public information on their respective portions of the program. NASA and ESA will undertake to coordinate with each other, and, as appropriate, with the other partners, in advance concerning public information activities which relate to each other's responsibilities or performance in the Space Station program.

Article 18 - Consultation and Settlement of Disputes

18.1. The Parties agree to consult with each other and with the other partners promptly when events occur or matters arise which may occasion a question of interpretation or implementation of the terms of this MOU.

18.2. In the case of a question of interpretation or implementation of the terms of this MOU, such question will be first referred to the NASA Associate Administrator for Space Station and the ESA Director of Space Station and Platforms for settlement. The Parties recognize that in the case of a question concerning the commitments made in this MOU to STA and/or MOSST, the consultations will be broadened so as to include the STA Director-General of the Research and Development Bureau and/or the MOSST Deputy Secretary, Space Policy Sector.

18.3. Any question of interpretation or implementation of the terms of this MOU which has not been settled in accordance with Article 18.2 will be referred to the NASA Administrator and the ESA Director General for settlement. The Parties recognize that in case of a question concerning the commitments made in this MOU to STA and/or MOSST, the matter will also be referred to the Minister of State for Science and Technology of Japan and/or the Secretary of MOSST.

18.4. Any issues arising out of this MOU not satisfactorily settled through consultation pursuant to this Article may be pursued in accordance with the relevant provisions of the Intergovernmental Agreement.

18.5. Unless otherwise agreed between NASA and ESA, implementation of decisions made pursuant to mechanisms provided for in this MOU will not be held in abeyance pending settlement of issues under this Article.

Article 19 - Entry into Force

19.1. Pursuant to the Arrangement Concerning Application of the Space Station Intergovernmental Agreement Pending its Entry into Force, which became effective on September 29, 1988, this MOU will enter into force after signature of both the NASA Administrator or his designee and the ESA Director General or his designee, upon written notification by each Party to the other that all procedures necessary for its entry into force have been completed.

19.2. Pending the entry into force of the Intergovernmental Agreement between the United States and the European Partner in accordance with Article 25 of that Agreement, the Parties agree to abide by the relevant terms of that Agreement.

19.3. If the United States or the European Partner withdraws from the Arrangement Concerning Application of the Space Station Intergovernmental Agreement Pending its Entry into Force, the corresponding Cooperating Agency will be deemed to have withdrawn from this MOU effective from the same date.

19.4. If, by December 31, 1992, the Intergovernmental Agreement has not yet entered into force between the United States and the European Partner in accordance with Article 25 of that Agreement, the Parties will consider what steps are necessary and appropriate to take account of that circumstance.

19.5. If the United States or the European Partner gives notice of withdrawal from the Intergovernmental Agreement in accordance with Article 27 of that Agreement, the corresponding Cooperating Agency will be deemed to have withdrawn from this MOU effective from the same date.

Article 20 - MOU Amendments

This MOU may be amended at any time by written agreement of the Parties. Any amendment must be consistent with the Intergovernmental Agreement. To the extent that a provision of this MOU creates specific rights or obligations accepted by another partner, that provision may be amended only with the written consent of that partner.

Article 21 - Review

Upon the request of either Party, the Parties will meet for the purpose of reviewing and promoting cooperation in the Space Station. In the process of this review, the Parties may consider amendments to this MOU.

Article 22 - Definitions and Explanations

22.1. In addition to the definitions specified in the Intergovernmental Agreement, the following definitions will apply to this MOU:

"international Space Station complex," also "Space Station," means the collection of elements listed in Article 3;

"manned base" means Space Station flight elements excluding the polar platforms and the MTFF;

"Parties" means NASA and ESA;

"partners" means NASA, ESA, STA and MOSST.

22.2. Explanation of the following terms may be found in this MOU in the Articles noted:

"Accommodations" - Article 8.1.d
"Command and Control Zone (CCZ)" - Article 8.1.a
"Common system operations costs" - Article 9.3
"Composite Operations Plan (COP)" - Article 8.2.d
"Composite Utilization Plan (CUP)" - Article 8.3.f
"Consolidated Operations and Utilization Plan (COUP)" - Article 8.1.c
"Flight elements" - Article 3
"Increment Plan (IP)" - Article 8.2.f
"Infrastructure" - Article 8.1.b
"Multilateral Coordination Board (MCB)" - Article 8.1.b
"Payload Operations Integration Center (POIC)" - Article 8.3.i
"Program Coordination Committee (PCC)" - Article 7.1.b
"Resources" - Article 8.1.d and Article 8.3.a.4
"Space Station Control Board (SSCB)" - Article 7.1.d
"Space Station Control Center (SSCC)" - Article 8.2.g
"Space Station-unique ground elements" - Article 3
"System Operations Panel (SOP)" - Article 8.2.a and Article 8.2.b
"Tactical Operations Plan (TOP)" - Article 8.2.f
"User Operations Panel (UOP)" - Article 8.3.d

DONE at Washington, this 29th day of September, 1988, in two originals in the English, French, German and Italian languages, each version being equally authentic.

FOR THE UNITED STATES
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION:

POUR L'ADMINISTRATION NATIONALE
DE L'AERONAUTIQUE ET DE
L'ESPACE DES ETATS-UNIS:

FÜR DEI NATIONALE LUFT- UND
RAUMFAHRTORGANISATION DER
VEREINIGTEN STAATEN:

PER L'AMMINISTRAZIONE
NAZIONALE PER L'AERONAUTICA
STATI UNITI:

Dale D Myers

FOR THE EUROPEAN SPACE
AGENCY:

POUR L'AGENCE SPATIALE
EUROPEENNE:

FÜR DEI EUROPÄISE
WELTRAUMORGANISATION:

PER L'AGENZIA SPAZIALE
EUROPEA:

NATIONAL RESEARCH COUNCIL
COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS
2101 Constitution Avenue Washington, D.C. 20418

COMMITTEE ON NASA SCIENTIFIC
AND TECHNOLOGICAL PROGRAM REVIEWS
Panel on Redesign of Space Shuttle
Solid Rocket Booster

December 21, 1988

The Honorable James C. Fletcher
Administrator
National Aeronautics and Space Administration
400 Maryland Avenue, S.W., Room 7137
Washington, DC 20546

Dear Jim:

I am pleased to submit herewith the final report of the National Research Council's Panel for the Technical Evaluation of NASA's Redesign of the Space Shuttle Solid Rocket Booster.

Since our last report, two missions of the National Space Transportation System have been completed, STS-26 and STS-27, employing the redesigned solid propellant rockets. The Panel has received a briefing from NASA and Morton Thiokol personnel on the results of post-flight inspections of the STS-26 boosters that were performed at Cape Canaveral Air Force Station and one member inspected the spent hardware while it was in Florida.

This report contains our evaluation of the redesigned boosters in STS-26 as well as our observations regarding the lessons to be learned from the experience of the redesign program.

The Flight of Discovery, STS-26

Initial inspections performed on the recovered hardware and preliminary analysis of data from flight instruments suggest that the redesigned solid rocket boosters performed as anticipated. Several problems did arise, however, that require NASA's attention:

(1) Small pieces of cork, which is used to cover external diagnostic instruments and their electrical leads, were lost during flight. One piece is thought to have damaged thermal tiles on the Orbiter. Deficiencies in the configuration and process of bonding the cork to the vehicle at Kennedy Space Center have been identified and modifications are being devised and adopted.

(2) Sooting has been reported within several internal joints in both nozzles. The causes and implications of this anomaly are not yet known. The problem was discovered after our last formal meeting and we do not have sufficient current information on it to comment on its seriousness. To develop an appropriate understanding of the phenomenon, NASA should review the results of static tests and carefully document its occurrence in future flights.

(3) A considerable number of pits, galls, scratches, and gouges were found on the surfaces of the interference fit in the case field joints of both the left and right boosters. Defects of this type had not been reported on the full-scale hardware used in ground tests, either short-duration simulations or full-duration static motor firings. Evaluation of these anomalies is being conducted at the refurbishment facility in Utah. Their occurrence could have important consequences for program costs, since removing them could change the dimensions of the hardware enough to make it more difficult to find mating parts that provide the desired interference fit.

Remaining Tasks in the Recovery Program

While STS-26 was a successful mission, work remains to be accomplished before we would consider the redesign program to be complete. We listed a number of the remaining tasks in our last report. Here we highlight the following:

(1) Redesign the aft skirt to meet the system requirement for design ultimate strength.

(2) Reconfigure the cowl vent holes in the nozzle to prevent the occurrence of differential pressure across the flexible boot.

(3) Determine the reuse potential of motor case segments. In addition to a hydroburst test after 20 cycles of pressurization, this task may require testing flown hardware in short-duration, full-scale test apparatus such as the Joint Environment Simulator since only flown hardware experiences the effects of re-entry, splashdown, and recovery.

(4) Modify the configuration of the pressure proof test to ensure that the case field joints experience more realistic stresses. In the current configuration, one case segment is capped by two rigid domes; consequently the ends of the segment do not experience stresses representative of the flight condition. The redesigned joint is more complex than the original design; since the joint experiences the highest stresses, it is imperative that the proof test subject the joint to the most realistic stresses. This goal may best be achieved by proof testing a case of two segments with a full field joint in the middle and factory joints mated to the domes.

(5) Continue pursuing improvements in materials and methods of bonding, notably of insulation to the case, of the polysulfide in the case-to-nozzle joints, and of the laminations of the flexible bearing, as well as methods of testing them nondestructively.

(6) Improve the accuracy and reliability of case measurements to assure the desired interference fit in the case field joint.

(7) Seek or develop alternative O-ring materials and processes and compatible corrosion-inhibiting greases that will operate satisfactorily without heaters. Any resulting changes in the design would have to be qualified before being introduced into flight hardware.

(8) Qualify the redesigned motor at the low end of its intended range of operating temperatures, as planned in the QM-8 static test.

(9) Continue to collect flight data in order to assess critically the performance of components of the redesigned booster. In addition to assessment of flight instrumentation data, these evaluations should include careful inspection of used hardware and a systemmatic assessment and documentation of the performance of seals, insulation, ablative materials, and metal components. The procedures should take account of the fact that in the case field joint and case-to-nozzle joint, upstream gas barriers will normally prevent combustion gases from reaching the primary seals, making it difficult to detect a degradation in the seals, materials, or surface finishes unless an upstream barrier fails. An important objective is to continue to improve the statistical validity of the data base.

Lessons Learned

The recovery from the Challenger accident evolved as a comprehensive redesign, testing, and qualification program. The Panel concluded that the program was well conceived and executed. Indeed, we believe that a number of important lessons have been learned from this experience that could well be applied to future NASA programs. In our view, the most important of these are the following:

Use of an Inherently Tolerant Design. In light of the complexity of the preparations for flight and the need to prepare components and vehicles under conditions that may be less than ideal, designs should be favored that are relatively insensitive to the level of skill and art required in manufacturing, assembly, or checkout. The design should be tolerant of small errors.

The redesign of the Shuttle booster was constrained by budget, schedule, hardware inventory, a desire to rely on the large existing data base to the extent possible, and compatibility with existing facilities and hardware with the result that it may be more sensitive to manufacturing, assembly, and checkout procedures than might otherwise be desirable. The resulting procedures are therefore costly and time-consuming. In the advanced booster design program, it may be cost-effective to devote considerable attention to achieving a design that is more tolerant of changes in variables that are difficult to control in materials, manufacturing, and assembly.

Understanding How the Design Works. In testing large and complex hardware systems such as the solid rocket booster, the major emphasis seems to be, first, on performance, next on overall reliability, and, last, on understanding how the subsystems and components actually work. From a programmatic perspective, understanding how a design works at the component level frequently carries a lower priority than just demonstrating overall system performance. Often, only when major components fail does the focus shift to developing a firm understanding of how the components actually perform over the full range of operating environments.

In response to the Challenger accident, the solid rocket booster recovery program initially focussed on determining how the originally designed parts had failed, understanding their operation, and establishing the margins of safety of the redesigned components. The unusually detailed analyses and tests run during the SRB redesign program frequently yielded surprises traceable to incomplete understanding of novel designs and the novel use of conventional designs. The growth in understanding was a major factor in the design improvement.

One of the important lessons learned from the post-Challenger experience is that heavy emphasis should be placed at the beginning of a new program in developing a detailed understanding of how subsystems perform in the total range of operating environments and in determining the margin of safety over maximum expected operating conditions of the component designs. In the current booster program, continued growth in understanding may help to reduce the large number of critical items that burden the "operational" program, thereby reducing operating costs and allowing full attention to what are truly the most critical items.

A Full Spectrum of Tests. Because of the inherent nature of solid propellant rockets, a statistically meaningful number of full-scale, full-duration, solid rocket motor tests simply cannot practically be accomplished prior to flight within any reasonable schedule and budget. NASA's strategy for developing confidence in the redesign was to employ a hierarchy of component and motor testing aimed at demonstrating nominal performance and establishing margins, product control, reliability, operational limits, and service life. The test program for the original Shuttle booster was less extensive than for many ballistic missile programs. For man-rated systems, test programs must be particularly thorough.

The redesign program has set a more rigorous standard for testing of material, component, and system function by including an extensive program of analysis; laboratory testing; subscale motor tests; full-scale, short-duration motor tests; and, ultimately, five full-scale, full-duration tests of complete motor assemblies. Emphasis was placed on gaining real understanding of how the system performed through a large number of laboratory and subscale tests coupled with analytical models, and then scaling to well instrumented full-scale, hot fire tests. In addition, several full-scale test articles were prepared to test the structural and assembly aspects of the new designs. In this way, significant confidence in the new designs could be achieved without many full-scale, full-duration tests. Furthermore, a subscale motor could be tested for a few tens of thousands of dollars while the costs of a full-scale, full-duration static test is likely to be in the millions to tens of millions of dollars. In the case of the redesigned joints, many subscale motors were tested with a number of design variants and with sufficient tests to begin to get some statistical confidence in the design, at least at the subscale level.

The results of those tests were often surprising, enlightening or disappointing, all of which show why the tests were needed. It is important that future programs recognize the need for a full spectrum of tests, and that NASA assure the capability to run them. It is also important that this philosophy of testing be continued in the current program until the operational limits, service life, and component reusability have been adequately determined. We believe that this basic testing strategy is a good one for development efforts of this type and may be successfully used in other NASA programs.

Early in the testing program, three Joint Environment Simulator (JES) tests of the Challenger field joint configuration added greatly to the understanding of the probable contributing causes of the Challenger accident and, in fact, appeared to duplicate closely the operation of the joint under the conditions of the failure. The experiments, each conducted at

25°F, were designed to study the importance for the sealing function of the manner in which combustion gases reach the O-rings. The results demonstrated that the worst situation arises when the gases are confined to a narrow jet that impinges on a seal. A jetting flow could occur in the original field joint design through blowholes that tended to form in the putty that was used to fill the space between mating segments. In one test, in which a blowhole was deliberately inserted in the putty, the performance of the joint appeared to be similar to that observed in the initial stages of the Challenger launch: blow-by of both the primary and secondary O-rings occurred, with black smoke visible on the outside of the joint at the point of the blowhole in the putty. These three JES tests and supporting dynamic laboratory measurements provided the basis for an assertion that there were three main problems with the Challenger joint that, together, resulted in the failure: a leak path through the putty causing a jet of combustion gas to impinge on a small area of the O-rings and rapidly erode them, a fast opening of a significant gap between the tang and clevis sealing surfaces during the ignition transient, and the inability of the O-rings to track the gap opening at the low temperature experienced at launch.

Two other simulators, the Nozzle Joint Environment Simulator and the Transient Pressure Test Article, were developed during the course of the program which, along with the JES, proved extremely valuable for improving understanding of the operation of specific redesigned components. The Panel believes that these test devices were of critical importance in the design verification program and that some of these test setups should be retained in an operational condition. In particular, we recommend that simulators be used in the future to verify the reuse potential of flown hardware, to demonstrate that the primary and secondary seals remain operational after long-term aging, and for verification testing of any future block changes in the redesigned booster. These types of test systems could also be of great value in the development and verification testing of future generations of solid rocket boosters.

Criteria for Success and Pretest Predictions. To assure the effectiveness of a testing program and to validate the technical understanding of a design, the Panel believes that both a statement of criteria for a successful test and a detailed analysis and prediction of how the hardware is expected to perform should routinely be prepared in advance of every major test. In the case of the booster development and verification program, we found that the team was conscientious in establishing specific pretest criteria for success and predictions of results. We believe that this discipline was an important factor in the program's success to date, that the discipline can be sharpened further, and that it should be applied diligently in future NASA programs.

Testing the Performance of Seals. The Panel is also a strong advocate of emphasizing testing that demonstrates the performance of design components at all levels under conditions more severe than would be encountered in flight. For the redesign joints, this testing included imposing purposely manufactured leak paths into test articles sufficient to guarantee that combustion gases would impinge on the respective barriers and seals for testing the performance of the new designs.

The ultimate test of the new joints prior to the return to flight was the full-scale, full-duration static test of the PV-1 motor. This test included pressure-assuring flaws to the primary O-ring in both the field joints and the case-to-nozzle joint, as well as intentional flaws in some of the internal nozzle joints and the case-to-igniter joint. Defects to simulate insulation edge separations were also intentionally introduced in several areas near the pressure-assuring flaws to evaluate the effects of poor insulation-to-metal bonding. This test represented a major departure from historical approaches to full-scale, full-duration ground testing of rocket motors and was debated for many months by the redesign team and our Panel.

We advocated the test because we were convinced that the requirement for redundant, verifiable, and independent seals should be confirmed in full-duration, full-scale testing. The test incorporated flaws that clearly were more severe than defects that can be expected to arise in the normal course of manufacturing and assembling the boosters but not be detected.

As the program proceeded, each of the flaws that was finally tested in the PV-1 motor was first successfully tested in subscale and then in full-scale, short-duration hardware. Thus, with each succeeding test, the team became more confident that the joint seal designs had truly redundant seals that performed as expected. The PV-1 test, which was performed on August 18th, was successful: full motor pressure did, in fact, reach the primary O-rings (through the flaws) but gas did not leak past the O-rings.

The Panel believes that careful preparation and demonstrations at subscale and intermediate levels prior to such a "high risk" test is critical to successful testing of this general type. Again, we believe that NASA might well apply this philosophy to other programs.

Validation of Analytical Computations. While extensive use of analytical models and computer-based computational methods is appropriate and necessary for developing and verifying space systems, we concluded that the current program achieved only mixed success in this regard. Models that were refined and validated through well instrumented subscale or component testing generally predicted the results of full-scale, full-duration testing rather well. However, models developed from "first principles" but not validated before full-scale testing often left something to be desired. This appeared to us to be particularly true of structural analysis where great emphasis was placed on large, complex finite element methods. The most obvious example was the redesign of the aft skirt where computer analyses led to a design that added hundreds of pounds of weight but did not significantly improve the structural margin of safety.

Computational results are no better than the physics of the models on which the analyses are based. There are many areas of design where the knowledge of the physics is too limited for reliable analyses (e.g., mechanical and thermal performance of ablatives), or where available computational codes are not adequate (e.g., analysis of plastic deformation in complex load situations or of heat transfer from viscous rotational two-phase flows). The experience in the SRB redesign program suggest a strategy that should be adopted in the future:

(1) Identify the areas where analysis is likely to be unreliable,
(2) Find and employ the best expertise available,
(3) Use the analysis to test for the sensitivity of results to poorly determined inputs, and
(4) Verify computed results by test.

We concluded that analyses, especially those whose objectives are to predict structural failure, must be verified by carefully planned and properly simulated experiments that are well instrumented. We suggest that NASA could improve its modelling capability by shifting some attention from computer program development to development of good engineering insight through simple, meaningful validation experiments.

Control of Processes and Materials. The redesign program has set new standards for control of materials and processes used in manufacturing the motor and its component parts, and for inspection of components, assembly operations, and the assembled product. While improving reliability, this has added substantially to cost and to production and assembly time. Some of these efforts may have been, or may later become, unnecessary as an acceptable degree of imperfection becomes clear. However, the enhanced control and inspection procedures have frequently shown the presence of defects that would not have been found in the past, some of which are still considered unacceptable.

There will no doubt be a push toward relaxation of quality control and inspection in the interest of economy and time or due to complacency. Potential improvements, particularly in process controls, may justify some reductions. It is absolutely crucial however that "relaxation" be a carefully planned, deliberate process in which lowered standards are only authorized after formal demonstration that safety and reliability are not compromised. Considering the nature of the Shuttle and its mission, standards for quality control and assurance should be the highest of all space systems.

Documentation of Lessons Learned. In light of the important lessons learned in the course of the redesign program, both technical and administrative, about large and complex engineering programs, we suggest that NASA commission an independent, professional technical history of the booster rocket recovery program to benefit future NASA--and possibly other national--programs of similar scope.

Risk Reduction through Product Improvement

Although our formal task is completed with the successful return to flight, the Panel has been briefed on NASA's plans for program activities beyond STS-26. We have also formed conclusions about what is needed for continued flight safety and have concerns about the adequacy of your plans in this regard. Before stating these concerns once again, it is appropriate to emphasize that the Space Transportation System consists of a very complex flight system, operating in a very hostile environment. It is not realistic to view the mission as risk-free. It is, however, reasonable to expect that a higher level of confidence can be acquired as more flight experience is obtained.

That confidence will only be gained from measured performance of the system (including data from quality control review and post flight inspection). Risk cannot be assessed without a data base, and confidence comes from large data bases, which cannot be provided from pre-flight tests alone. It is standard practice in the aeronautical industry to monitor flight performance (from components to systems to the vehicle) and to make modifications when the data base indicates that safety margins are below design requirements or potential failure modes are not adequately treated in the design.

The need for such practices is even more important in the Shuttle system because the safety margins are lower than in the aeronautical industry (due to considerations of weight) and the opportunity to develop a performance data base is orders of magnitude more limited. This message was dramatically conveyed by the Challenger accident and the conditions leading to it. The thorough redesign and verification effort since then reflect a new set of standards within NASA and the space industry. It is important that these standards be continued in the flight program, and that budgetary, manpower, and facilities policies be consistent with that objective.

Some specific recommendations for effective control and reduction of risk are:

(1) Maintain a technically competent team of personnel that is familiar with booster design to evaluate, maintain, and/or improve quality control, assembly, launch operations, post-flight evaluation, and questions of service life.

(2) Provide for measurements during flight for as long as program engineering and safety personnel perceive the need (i.e., get the data base).

(3) Maintain a supporting program of ground testing that will provide for product quality control and for validation of changes in material, manufacturing, and design related to product reliability. This program should include maximum use of the "Test Evaluation Motor" firings for the these purposes.

(4) Provide enough flexibility in the flight program to introduce adequately evaluated material, manufacturing, and design improvements expeditiously when accumulating results indicate unanticipated risk.

(5) Insulate the budget for the above activities from competitive pressures from the flight program or advanced solid rocket motor programs and reduce their support only in the context of statistically significant base of measured flight performance.

Organizational Issues

At times, some organizational issues seemed to have impeded the smooth progress of the redesign effort. For example, we observed problems with calculation and dissemination of loads within the program. Information about design loads was difficult to obtain and almost always in a state of flux. We believe that the designers of components of solid rocket booster should not only have intimate understanding of the loads but also be sufficiently knowledgable to challenge the methods and results of the calculations supplied by others. The organizational and management issues pertinent to the calculation and dissemination of loads should be reviewed by NASA.

Finally, as we have recommended previously, independent responsibilities should be firmly established for setting design requirements and standards and for carrying out the design. The objective should be to ensure a system of checks and balances in the inevitable interplay between design and requirements.

Acknowledgments

Finally, Jim, all of the members of the NASA/contractor team responsible for the redesign of the solid rocket booster have earned the appreciation and congratulations of the Nation for their tireless dedication leading to the return to flight of the Shuttle in the face of intense public scrutiny. We join in expressing our own thanks, particularly because we could not have discharged our responsibilities without their earnest cooperation and support.

We are especially grateful to John W. Thomas, of NASA's Marshall Space Flight Center, and Allan J. McDonald, of Morton Thiokol, Inc., who bore a primary responsibility for making the engineering judgments required in the redesign program and the burden of convincing us that they were right--or accepting our recommendations. We owe a special debt of gratitude to Russell Bardos, of NASA's Office of Space Flight, for assuring that we had the information we needed to fulfill our charge, guiding us through the program's organizational structure, and providing excellent liaison between the Panel and the respective levels of NASA.

Sincerely,

Guy

H. Guyford Stever
Chairman

cc: Adm. Richard H. Truly
Panel Members

CHALLENGER ACCIDENT RECOVERY

Staff Report*

January 1988

* Dr. George Uriano, Congressional Fellow
Subcommittee on Space Science and Applications
Committee on Science, Space, and Technology
U.S. House of Representatives
Washington, D.C. 20515

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Appendix

Summary of Recommendations in the Committee's Challenger Accident Report ....
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EXECUTIVE SUMMARY

A. BACKGROUND

Two years ago, the American people learned in a devastating manner that neither NASA nor its contractors are immune from making serious mistakes and that, as a consequence, the Space Shuttle was not as reliable as had been assumed. The comprehensive investigations that were conducted by the Rogers Commission and the Committee on Science, Space, and Technology found numerous examples where the hardware designs and operating procedures that were being used within the Shuttle program were critically deficient.

Building on these findings, both the Rogers Commission and the Committee formulated an extensive group of recommendations in order to correct these deficiencies. A summary of the recommendations that were made by the Committee are presented in the Appendix of this report.

Since issuing the report on the Committee's investigation of the Challenger accident, the Committee has been actively involved in monitoring the progress that NASA and its contractors have been making in correcting past deficiencies and preparing the Shuttle for a return to flight status.

In addition to these oversight efforts, a number of other groups have also been actively monitoring various aspects of NASA's recovery progress. These groups have included the following:

- The National Research Council Panel on Technical Evaluation of the Redesign of the Space Shuttle Solid Rocket Booster,
- The National Research Council Committee on Shuttle Criticality Review and Hazard Analysis Audit,
- The Aerospace Safety Advisory Panel (ASAP),
- The NASA Advisory Council (including its Panel on Issues of a Mixed Fleet), and
- The National Research Council Panel on Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization.

The Committee has communicated with these groups on both a formal and informal basis throughout the recovery period. The Committee held several days of hearings at which these organizations were asked to formally testify regarding how they viewed the progress that was being made by NASA.

The purpose of this report is to summarize the results of those hearings and the findings that have emanated from them.

B. MAJOR FINDINGS

From these hearings and the other elements of the Committee's oversight activities, the general view is that NASA has made substantial improvements since the accident and that the overall movement of the Agency during the recovery program has been in the right direction. However, there were still some areas of continuing concern to the outside review panels and the Committee. In some of these areas, the success of NASA's initiatives is yet to be determined.

A review of the progress that NASA has made in the Shuttle flight recovery program can be conveniently divided into the six categories that follow.

Program Management, Organization, Communication, and Technical Decision-Making

There appears to be general agreement among the various review panels that NASA has made considerable progress in resolving many of the management, organizational, communications, and procedural problems that contributed to the Challenger accident. The extensive changes that have been made in personnel, organizational structure, and management controls should significantly improve the management and operation of the Space Shuttle program in the future.

On the other hand, whether these changes and improvements will be totally sufficient is still an open question. Additionally, it is not yet clear that the "attitude problem" of personnel throughout the Shuttle program (in dealing with schedule and cost pressures, and in the implementation of quality and safety standards) has been completely resolved, in spite of all of the positive changes that have been made.

Finally several of the witnesses expressed the view that an attitude of "safety first" and "schedule second" should be implemented and continuously reinforced throughout the entire life of the Shuttle program.

Safety, Reliability, Maintainability, and Quality Assurance

The Committee has noted that NASA has established a much stronger and comprehensive SRM&QA program throughout the Agency. On the other hand, while these improvements offer obvious advantages, their ultimate effectiveness will depend on the program and line managers that are responsible for their application as a part of their day-to-day activities. Clearly, the "attitudes" of NASA and contractor personnel regarding safety and quality are as important as having good practices and procedures in place.

NASA has also made noticeable progress in the following areas: its review and reevaluation of critical Shuttle components and in conducting appropriate "Failure Modes and Effects Analyses;" its improvements in Shuttle processing operations; and its attention to the problem of maintaining an adequate inventory of spare parts and minimizing the necessity for "cannibalization" of hardware from other Orbiters.

Other areas that continue to be of concern include the following: the lack of structural loads data for the Orbiter and the Solid Rocket Motor; a lack of significant progress in implementing a comprehensive Shuttle risk management program which utilizes probabilistic risk assessment (PRA) techniques in evaluating the relative risk or importance of various problems or courses of action; a continuing lack of understanding of why the important deficiencies in the testing and certification of the Solid Rocket Motor went undetected prior to the accident; and a continuing lack of initiatives to modify contract incentive provisions to place more emphasis on quality and safety rather than schedule and cost.

Solid Rocket Booster Design, Manufacturing, and Use

There is a general consensus that the newly designed joints in the Solid Rocket Motor are a marked improvement over the original designs. It is also generally agreed that NASA is making substantial progress in redesigning other critical components within the Booster. Further, the newly developed techniques for non-destructive testing that will be applied in inspecting the Solid Rocket Motor in the future should result in an improvement in available safety margins.

Additionally NASA has adopted a procedure of predicting the outcome of each Solid Rocket Motor firing before the test is conducted.

Though all of these are positive indicators, their effectiveness will have to await the conclusion of the ongoing testing program.

Space Shuttle Main Engine Design and Use

NASA has made considerable progress in evaluating, understanding, and fixing a variety of problems that have existed in the Main Engine. On the other hand, some problems with cracks and vibration appear to require additional attention.

The Aerospace Safety Advisory Panel in particular was disappointed that progress on the development of an improved margin engine has gone very slowly because of limited funds and the lack of available test stands. The Panel felt that it would be prudent to operate the Main Engines at a thrust level no higher than 100 percent until the Phase II engines have accumulated significant flight data.

Inasmuch as the Main Engines are one of the highest risk elements of the overall Space Shuttle system, the Main Engine program should be characterized by aggressive test and margin enhancement activities and conservative flight operations.

Orbiter Landing System Design and Use

The comments by the witnesses at these hearings did not directly relate to this area of oversight. However, the Aerospace Safety Advisory Panel has raised concerns about this area in several of its annual reports. Additionally, the reports and briefings that NASA has given the

Committee since the accident have allowed the Committee to keep abreast of the progress that is being made in this area.

It is clear from these reports that a lot of activity is underway in redesigning and improving the landing, braking, and steering systems on the Orbiter. Though it appears that progress is being made, the success of these efforts will have to await future testing and then ultimate use in flight.

Shuttle Flight Rate Pressures and Launch Decision Procedures -- and the Use of Expendable Launch Vehicles

In the Committee's investigation report, it was concluded that NASA's drive to achieve a launch rate of 24 flights per year created pressure throughout the Agency that directly contributed to unsafe operations -- and subsequently, to the Challenger accident. The Committee therefore has attached a high degree of importance to initiatives that will reduce Shuttle flight rate and launch pressures in the future.

There has been mixed progress within this problem area. On the one hand: NASA has announced that it will begin to use expendable launch vehicles for some of its payloads; and the many commercial and defense payloads that have been removed from the Shuttle's launch manifest will help to reduce the demand for a higher flight rate.

On the other hand: NASA continues to project that it will be able to achieve launch rates that panels of outside experts think are unrealistically high; the Agency has been slow to purchase expendable launch vehicles; and NASA has indicated a willingness to use the Space Shuttle over the long-term for some launch activities that do not require the presence of man, such as placing TDRS spacecraft into orbit.

Regarding this last point, witnesses from the National Research Council, Aerospace Safety Advisory Panel, and NASA Advisory Council agreed that Space Shuttle launch activities should be preserved for missions that require the presence of man. The risk to the crew and the potential for loss of a scarce national resource (i.e., an Orbiter) are viewed by these witnesses as not justifiable for missions that do not require the presence of astronauts. Under current circumstances, the use of the Shuttle for missions that do not require man would also constitute a misallocation of scarce resources that should be preserved for performing manned missions.

NASA's desire to maximize the flight rate may stem from a belief that such a utilization scheme is cheaper than minimizing the use of the Shuttle and maximizing the use of expendable launch vehicles. Referring to this point, witnesses from the National Research Council and the NASA Advisory Council expressed the view that in terms of total national costs, expendable launch vehicles are no more expensive than the Space Shuttle. Because of the importance of this point, and the apparent inconsistency between NASA and outside experts regarding its validity, it is appropriate that the Agency should study in greater detail the total cost perspective and budgetary impact of a mixed fleet.

As a final observation, there has been a marked tendency for NASA to persist in referring to the Space Shuttle as "The Space Transportation System." Though this is not as significant as other issues raised in this report, it may reflect an attitude counter to a fundamental finding from the Committee's accident investigation report. That is, the NASA view that the Shuttle was the "be-all" and "do-all" of space transportation was part of the "attitude problem" that ultimately brought the program to disaster.

C. CONCLUSIONS

It is clear that NASA has made definite progress in recovering from the tragic loss of the Challenger. However, it is also clear, that much additional work remains to be done.

The next year will be one of the most important periods in the history of the U.S. civilian space program. The success or failure to resolve the numerous problems that have been encountered by the Space Shuttle will not only determine the long-term viability of the Shuttle as a major and unique launch system, but may also largely determine the long-term future viability of the civilian space program and of NASA itself. The Committee's oversight responsibilities for the Space Shuttle and other NASA programs during this critical period will play an important role.

The successful resumption of Shuttle flights is the first step in a renaissance for the civilian space program. A safe and effective Shuttle flight program is essential to the launching of many important payloads such as the Hubble Space Telescope, space science and applications experiments, planetary probes, and eventually the construction and long-term support of the Space Station, as well as maintaining an overall leadership position for the U.S. space program in an increasingly competitive international arena. A failure in the Shuttle flight program could cause unprecedented programmatic, budgetary, and political problems for the civilian space program.

The Committee on Science, Space, and Technology will continue to review the Shuttle recovery program and the Nation's access to space as we enter this most critical phase in the civilian space program. There is much to be accomplished in the coming months and years. The intent of the Committee is to be a positive force in the completion of this work.

A major goal of the Committee's oversight is to see that the Space Shuttle is restored to a safe and efficient flight status. An additional goal is to restore the civilian space program of the United States to a position of world leadership. In order to achieve these goals, the cooperation of NASA, its contractors, and policy makers elsewhere in the Administration will be essential.

I. INTRODUCTION

In the aftermath of the Space Shuttle Challenger accident on January 28, 1986, extensive investigations of the causes of the accident were carried out by the Presidential Commission on the Space Shuttle Challenger Accident (hereafter referred to as the Rogers Commission) and the Committee on Science, Space, and Technology of the House of Representatives. The reports[1],[2] issued by these two groups contained a large number of findings concerning the causes of the accident and numerous recommendations for resuming safe flight.

The National Aeronautics and Space Administration (NASA) has issued two reports [3],[4] which provide specific responses to each of the recommendations contained in the accident reports of the Rogers Commission and the Committee and also summarize the progress made in the Shuttle recovery program since the accident. These reports indicate that considerable progress has been made in redesigning, testing, and recertifying critical hardware to ensure greater safety and reliability in the Shuttle after it resumes flying. A number of significant management and organizational changes have also been made at NASA to improve technical decision-making and to ensure that safety, reliability, and quality assurance (SR&QA) systems operate more effectively throughout all NASA programs in the future. However, much remains to be accomplished to increase the safety of Shuttle flights and to permit the Shuttle to be treated as an operational system.

The Committee on Science, Space, and Technology is continuing to monitor the progress made in the Shuttle recovery program. Two hearings held on April 29-30, 1987 were an important part of this oversight process. At these hearings, testimony was received from witnesses representing five special NASA or National Research Council (NRC) panels or committees (hereafter the terms "panel" and "committee" will be used interchangeably) that have been monitoring and/or evaluating important technical activities and policy issues associated with the Shuttle recovery program. The panels represented at the hearings were the following:

- NRC Committee on Shuttle Criticality Review and Hazard Analysis Audit,
- NASA Aerospace Safety Advisory Panel (ASAP),
- NRC Panel on Technical Evaluation of the Redesign of the Space Shuttle Solid Rocket Booster,
- NRC Panel on Post-Challenger Assessment of Space Shuttle Flight Rate and Utilization, and
- NASA Advisory Council Panel on Issues of a Mixed Fleet.

In his opening statement, Chairman Bill Nelson (D-FL), of the Space Science and Applications Subcommittee, stated:

> "Today, we are going to continue our series of hearings on the Shuttle recovery effort. The objective is to ensure that when the Shuttle returns to flight status, it will be fully ready to conduct its operations in as safe a manner as possible. The purpose of these hearings is to receive testimony

> from independent review panels that have been monitoring NASA's recovery. By learning from the insights of these groups, we hope to be better prepared to conduct our oversight responsibilities in this area. We have to maintain vigilance over this program."

Congressman Robert Walker (R-PA), Ranking Republican Member of the Space Science and Applications Subcommittee, added in his opening statement:

> "Some of us are concerned about what the status of the Shuttle will be as we move toward the first flight. We are also concerned about some of the things that we still hear coming out of the agency about flight rates and the various component parts of the Shuttle. I think the hearings should give us a chance to help clarify some of the questions that are still on the minds of some members of this subcommittee, as well as begin the process of assuring ourselves that in the future, safety will be the principal concern on all Shuttle flights."

Section II of this report is an extended summary of the testimony of the witnesses representing the panels. Section III reviews the progress being made by NASA in addressing some of the major problems in the Shuttle program identified in the Committee Challenger accident investigative report, which relate to the specific areas of responsibilities of these panels.

II. EXTENDED SUMMARY OF WITNESS TESTIMONY

During the two days of hearings, witnesses representing five NASA and National Research Council Panels testified on issues related to the Space Shuttle recovery program. The first day of the hearings focused on the Shuttle criticality review and hazard analysis processes and a general review of the Shuttle safety system by the statutory NASA Aerospace Safety Advisory Panel. The second day concentrated on important issues related to the Space Shuttle solid rocket booster, flight rate, and the use of expendable launch vehicles to complement Shuttle payload launches.

The following is a brief summary of each witness's testimony.

A. National Research Council Panel on Shuttle Criticality Review and Hazard Analysis Audit

Alton D. Slay, General U.S.A.F (Ret.), Chairman, Committee on Shuttle Criticality Review and Hazard Analysis Audit, of the National Research Council, Aeronautics and Space Engineering Board, testified concerning the committee's interim findings on the Space Shuttle risk management program. The primary function of the committee is to review and evaluate risk management processes. The committee operates under the assumption that if Shuttle risk management policies, procedures and processes are good, then the Shuttle operations should also be good.

An interim committee report was presented to NASA on January 13, 1987. The seven major recommendations contained in the Gen. Slay's testimony are summarized below:

- NASA management should ensure the certain and timely feedback of system performance and test data to subsequent program decisions, such as in the Failure Modes and Effects Analysis (FMEA) process.

- "Waiver authority for all the most critical items now rests with NASA headquarters. The committee believes that Headquarters should focus its attention on the most important items, determined by the suggested use of priorities of critical items, and delegate decisions on the others to lower management levels."

- Some mechanism for assigning priorities to critical items, should be developed, which takes into account the probability of occurrence of an event.

- An integrated Space Transportation System analysis and assessment process should be incorporated into NASA's risk management system "to assure assessment of the truly critical safety elements in the STS."

- More use should be made of quantitative risk assessment techniques to assess the relative risk or relative importance of different courses of action. "However, we do not wish to suggest that NASA subordinate technical judgement to numerical analysis."

- A close linking between the STS engineering change activities and the Shuttle FMEA process should be assured.

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- O NASA should consider modifying the current definition of critical items to account for probability of failure.

The committee will continue its audit by examining other aspects of the Shuttle risk management process including launch commit criteria and waivers, the functioning of the new NASA Office of Safety, Reliability and Quality Assurance, the Shuttle structural analysis activities, software risk management, and the effect of payloads on safety. The committee will submit a final report to NASA in late 1987.

In his concluding remarks, General Slay noted:

> "While we recognize that it is not possible a priori to guarantee mission success and flight safety, through this review and audit we hope to provide a reasonable and responsible level of assurance of flight safety for the Space Shuttle. The Committee has been favorably impressed by the dedicated effort and beneficial results obtained thus far by NASA and its contractors from the risk management system. We are very appreciative of the frank and open manner in which they have worked with the Committee. Our suggestions have been received in a very responsive manner as exemplified by Dr. Fletcher's response to the Committee's letter report..."

Response To Member's Questions

The Member's asked Gen. Slay a number of questions concerning issues related to NASA safety, reliability, and quality assurance practices and the utilization of expendable launch vehicles. The questions and answers are summarized in this section.

NASA Management and Organization Changes

Chairman Bill Nelson (D-FL) asked whether NASA's recent organizational and procedural changes in the areas of safety, reliability, and quality assurance were adequate? General Slay responded:

> "Well, Mr. Chairman, only time will tell whether they are adequate or not. I will say this without any reservation -- it is certainly a move in the right direction. I think from what I understand of NASA's history, we have had a sort of dip in this area... With the establishment of George Rodney's office at the Associate Administrator level, I think it gives a lot of visibility to these kinds of things. I strongly applaud NASA for doing that, but whether or not it turns out to be organizationally adequate, only time will tell."

Testing and Certification Procedures

Mr. Nelson then asked whether the testing and certification procedures currently being employed by NASA were adequate to ensure the safe operation of flight hardware? General Slay indicated that he didn't like the word "ensure" because it is very difficult to ensure that anything is going to come back on the ground in one piece. He further stated:

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"...from my point of vantage, they (NASA) are doing all the right things. They are going about the recertification and the revalidation in the proper way, with the few concerns I have mentioned to you in the area of looking at the Shuttle as an overall system in the failure modes and effects analysis area."

Hardware Fixes

Mr. Nelson asked Gen. Slay for his opinion regarding the proposed Shuttle hardware fixes. Gen. Slay responded:

"those are very well considered and needed engineering changes. I think that they have done a good job of looking at this from and engineering point of view. We have found nothing at all to indicate to us that they are on anything but the right track."

Congressman Robert Walker (R-PA) asked whether the panel was assured that each time a change was made in a component of the Shuttle, a full assessment of how that change might affect the entire system is also made? General Slay stated:

"We have been completely assured of that... and we are now certifying that the (reassessment) process is in effect and in place."

Spare Parts and Cannibalization

Mr. Nelson asked whether spare parts and cannibalization might still be a problem. Gen. Slay stated that he was:

"...opposed to cannibalization except in an extremely urgent situation. It is wasteful of money, it is wasteful of effort, and it also introduces potential problems and potential failures..."

Safety Incentives in Contracts

Mr. Nelson then asked whether NASA's present method of contracting gives enough incentives for quality and safety? Gen. Slay stated:

"I really haven't looked at that... I believe that profit levels are high enough that incentives ought to be there, but whether they are, I don't know."

Use of Probabilistic Risk Assessment Techniques

Congressman Harold Volkmer (D-MO) expressed a concern that the use of probabilistic risk assessment (PRA) rather than technical judgement as the basis for making important decisions might cause problems. Gen.Slay indicated that:

"Probabilistic risk assessment from a management point of view is a tool. It helps you to direct your attention on something that is more likely to occur than something else. It doesn't say that the discreet numbers that you come up with are, in and of themselves, correct... You must rely on technical judgments -- good, sound

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> engineering judgments. But we think that these engineering judgments can be better applied by using this tool..."

NASA Technical Decision-Making Competence

Mr. Volkmer then asked whether NASA has the engineers that are qualified to properly exercise technical judgment? Gen. Slay stated "they do have that kind of technical judgment." However he indicated that NASA may not have sufficient statistical engineering capability.

Utilization of Shuttle and ELVs

Congressman Ron Packard (R-CA) asked General Slay to suggest changes in the utilization of the Shuttle. Gen. Slay responded:

> "We cannot afford in my opinion to rely on one mode of transportation to space. We must have ELVs, and I believe that most everyone in the business has come to a similar conclusion."

He went on to state that the Air Force has:

> "come to grips with this and have clearly established a policy that we will do a considerable amount of space transportation with expendables instead of planning 100% on the Shuttle... I think this is a wise move. I believe that NASA is moving in that direction, and I applaud that move..."

Mr. Packard followed up this question by asking whether NASA should take a more aggressive role in the procurement of ELVs? Gen. Slay gave his personal opinion:

> "If by the term 'aggressive,' you mean should NASA be aggressively pursuing the ELV option, I would say absolutely yes... Whether or not you mean by 'aggressive' doubling their effort or tripling their effort, I am not prepared to say...from my knowledge of what NASA is doing, they are proceeding with some deliberate speed in the direction of ELVs."

Mr. Packard then asked whether NASA should request special funding for ELVs. General Slay indicated he hadn't reviewed that issue and would have to "pass" on the question.

Crew Escape System

The issue of the viability of a crew escape system was then raised by Mr. Nelson. Gen. Slay commented:

> "I will say this, Mr. Chairman, without any fear of being wrong -- every astronaut that ever intends to fly on the Shuttle would like there to be some sort of crew escape.... However, if it is going to break the back of the Shuttle from a financial point of view -- I think I would also speak for every astronaut -- they wouldn't want us to break the back of the Shuttle."

B. NASA Aerospace Safety Advisory Panel

Mr. Norman R. Parmet, Deputy Chairman, NASA Aerospace Safety Advisory Panel (ASAP), testified on the recent findings and recommendations of this statutory panel related to Shuttle recovery issues. He was accompanied by panel members: John G.Stewart, Melvin Stone, and Charles J. Donlan. Also accompanying him were panel consultants: Seymour C. Himmel, and Norris J.Krone. The 1986 ASAP Report[5] was submitted to Congress in March 1987 and a special report[6] entitled "Lessons Learned" was also made available at the hearing.

Mr. Parmet indicated that the Shuttle recovery program was acceptable to the panel and emphasized the continued need to place "safety first and schedule second." Management changes made since the accident should strengthen NASA. However some words of caution are necessary. The following specific points were emphasized in his oral and written statements:

- "The absence of a clearly articulated national commitment to space development and exploration -- in conjunction with the availability of alternative launch systems of other nations -- has created a situation where NASA could be tempted to rush the Space Shuttle back to flight status. The need to keep the United States competitive in the international market for space flight services cannot be permitted to override a commitment to 'safety first; schedule second.'"
- "...excessive reliance by NASA management on external and internal review groups runs the real risk of destroying NASA's initiative and self-confidence..."
- "The panel also cautions against placing excessive reliance upon the shoulders of the Office of Safety, Reliability, and Quality Assurance (SR&QA)." SR&QA must be built into the system rather than inspected in after the fact.
- "The recovery program is viewed as acceptable. However, it is important that planned work continue to completion."
- NASA must provide additional analytical tools to prioritize specific problem areas. ASAP supports the probabilistic risk assessment (PRA) approach. However PRA should not be used as "a bottom line for the risk of a launch."
- The paperwork systems at Kennedy Space Center (KSC) "require upgrading to assure that documents are current, easy to understand and easy to use."
- The Solid Rocket Booster (SRB) joint redesign is a "marked improvement over the original design but may have a problem with mating, demating, and re-use." The success of the redesign program will be largely determined by the results of the test program. "A more complete definition of the certification test program is required to determine its adequacy." During the first year of resumed Shuttle flights, "the SRBs should be heavily instrumented to obtain both structural and performance data and these data should be considered as part of the certification program." NASA should proceed with the parallel

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development of alternative designs for the case-field and case-nozzle joints such as the proposed "Langley" design (or its equivalent) for the case-field joint and the "Hercules" design (or its equivalent) for the case-nozzle joint.

- A Flight Readiness Firing (FRF) of STS should be performed "to assure integrity, operational performance, measurement of twang to set SRB firing timing, exercise of launch control center and its personnel, and abort shut-down." "The FRF was recently approved by NASA."

- "Structural loads and resultant structural stress conditions continue to crop up as a concern, particularly in the mid-fuselage area and portions of the wing." The concern is with the accuracy of the loads cycle analyses and the measurement of actual loads during ascent and descent.

- The panel is concerned with the ability to "replace and/or repair aging Line Replaceable Units (LRUs), assurance of configuration control and currency of engineering drawings, applicability of ground support equipment and test and/or checkout units."

- The most significant problems associated with the SSMEs, which must be resolved before flight, are "high-pressure turbopump blade cracks, high-pressure fuel turbopump coolant liner buckling, main combustion chamber coolant outlet neck cracks, and 4000 Hz vibration phenomenon in the thrust-cone region." "The panel was disappointed to find that work on the precursor (improved margin) engine is proceeding very slowly because of limited funds and lack of test stand availability." The SSMEs should be "constrained to operate at 104 percent rated thrust or less, except under emergency conditions." "It would be prudent to operate at 100 percent thrust until the Phase II engines have accumulated significant flight data." NASA and the SSME contractor should "continue the development of improved methods for demonstrating critical operating failure mode margins and the more rigorous risk assessment analytical procedures." The term "Failure" should be defined as "a violation of any of the governing design criteria for a component rather than as an event such as structural failure."

- "There are policies and activities associated with launch processing where achievement of more routine and predictable operations would enhance safety and reliability. For example, a freeze should be declared on non-mandatory changes during the period before the next launch...", and "adhering to a launch schedule that best fits the hardware redesign and reverification programs..."

- There is a danger of "oversight gridlock" -- the situation where "institutionalized second-guessing through myriad review panels, and oversight committees dilute the sense of responsibility, discipline, and accountability that properly resides with line managers." "The danger in placing undue reliance on an elaborate structure of review and oversight is that it could become a justification for not doing the job correctly in the first place."

Response to Member's Questions

A summary of the important points made by the Member's and the various witnesses representing the ASAP follows.

Program Coordination and Organizational Communication

Mr. Nelson asked Mr. Parmet to comment on a concern expressed in the ASAP Annual Report: "The NASA Centers must subordinate parochial interest and develop a willingness to pull together." Mr. Parmet indicated that statement was based on observations made last year. He further stated:

> "We see a great change in the sense of awareness of responsibility and we think that things are changing now. There is far more cooperation between and among Centers. There is far more willingness to listen, and they are working together far better than we have ever seen them before."

Mr. Nelson then asked about the statement of the Panel, which indicated "that top NASA and Shuttle processing managers need to communicate more directly with the launch processing workers." Mr. Parmet and Mr. Stewart indicated that six Panel members had interviewed "top people" and "working guys" at the launch facility. They stated that a number of Shuttle Processing Facility and Vehicle Assembly Building technicians had indicated that:

> "often the communications as to what they were supposed to do on any given work assignment simply were not clear... If they were clear, they were wrong, and so there was a lot of rework having to be done simply because the initial set of instructions was not correct."

Mr. Stewart went on to state:

> "...it appeared that the channels between the supervisors -- the engineers employed by the Shuttle processing contractor -- and the workers simply were not as active as they ought to be."

He indicated that the Panel's most recent visit to KSC found the situation to be getting better.

> "There is some improvement, and so the trend is in a positive direction, but you've got to keep working at it."

Shuttle Flight Rates

Mr. Volkmer asked a series of questions dealing with the flight rates that might be achieved with a 4-Orbiter fleet. Mr. Parmet indicated that he served on the panel chaired by Dr. David (at the National Research Council), which was concerned with this issue and agreed with that panel's conclusions. He went on to state:

> "If you had four (Orbiters) today, it wouldn't make any difference (with regard to the flight rate). In my view, you would still build up very slowly because after this accident, everybody is going to

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> start treating this as an experimental and development program once again until everybody is sure of the direction they are heading. Then they will build up the rate again. We're back to flight testing in effect."

Adequacy of Solid Rocket Booster Redesign

Mr. Volkmer asked the panel members to elaborate on their comments concerning improvements in the SRB design. Mr. Stone indicated that the design was a "marked improvement." He further indicated that the rotation of the field joint had been reduced from about 45 mils to about 9 mils. In order to further reduce the rotation, a different design would be needed and take possible 3 to 5 years to develop.

Reuse of Solid Rocket Booster

Mr. Volkmer followed up with a question concerning whether problems were expected with reuse of the SRBs. Mr. Stone indicated a number of tests were being made to evaluate the problem. However, any final conclusions would have to wait for examination of hardware used in flight.

Future Advances in SRB Safety and Performance

Mr. Nagle then asked the Panel to comment on NASA's proposal to develop an Advanced Solid Rocket Motor (ASRM) and whether the ASRM would result in improved safety? Mr. Stone indicated that safety and reliability could be improved and that the ASRM could result in extra lifting capabilities of around 15,000 pounds, which would enable the Shuttle to meet its pre-Challenger accident lift performance requirements of 65,000 pounds into low earth orbit from KSC. Mr. Stone emphasized that the redesigned SRB would be "safe enough" after all tests are completed and with proper flight instrumentation.

Mr. Donlan then added that the original decision was to use pressure-fed liquid rocket boosters in the Shuttle, which have the advantage of throttle control and throttle termination. Because such a system would have cost a half billion dollars or more than solid rocket boosters to develop, the decision was later made to use SRBs. Mr. Donlan indicated that he was happy to see NASA is including a study of pressure-fed liquid boosters in the ASRM proposal.

Mr. Nagle asked whether it wouldn't be better to spend the nearly one half billion dollars needed for the ASRM on ELVs and/or the development of a Heavy-Lift Launch Vehicle? The Panelists indicated that the situation was complex and expressed some differing opinions. They agreed that a coordinated military/NASA plan should be developed. Mr. Krone expressed his opinion:

> "...it would be advisable for us, since the Shuttle is a relatively old system in a technology sense, to go with a newer technology alternative, at the same time upgrading the current systems on the Shuttle to make it as safe as possible and to operate at as high payloads as possible. ...you would be looking at advanced manned systems, but for now I think from a technology standpoint, it is, again opinion, more advisable to go with an unmanned alternative."

Second Source for SRB

Mr. Nagle then followed-up by asking: "Some observers have suggested that the cost of the solid rocket motors would be reduced, while their safety and reliability would be enhanced, if NASA would contract to have two competing suppliers of these motors rather than buying them only on a sole source basis -- what do you think of that?" Mr. Parmet stated his personal opinion that a second production source "is going to cost you a hell of a lot more money than it would with a single source." He preferred that two companies compete to develop a new product with the winner of the development competition to become the sole producer.

Mr. Stone pointed out the current contractor for the redesigned SRB is "way up on the learning curve" and it would be difficult for another contractor to compete.

Space Shuttle Main Engine

Mr. Nelson asked about a recommendation of the ASAP concerning operational thrust levels of the SSMEs. The ASAP concluded that changes being made in the main engine do not add any significant improvement to its margin to failure and that the engines should be operated at power levels no higher 100 percent of rated thrust. Mr. Himmel clarified the Panel position by indicating that it would be prudent to operate at 100 percent until some flight time was experienced. If payloads and trajectories do not require 104%, it would be prudent to set thrust levels at a less stressful lower level. Mr. Himmel also suggested the use of improved methods for demonstrating failure mode margins and subsystem level testing.

Spare Parts, Cannibalization, and Maintenance

Mr. Nelson then asked about the statement in the report that the Kennedy Space Center (KSC) needs adequate budgets so that they can have a sufficient inventory of spare parts. Mr. Parmet indicated that in the past, money appropriated for spare parts was not used to buy spare parts because NASA needed the money for other purposes. He further indicated that "there is always going to be some measure of cannibalization" and cited the experiences of the airline industry where cannibalization runs at a rate of 3 or 4 percent rather than the 50 percent experienced in the Shuttle program. He further stated that he believed that "funds for NASA's logistics program are in place and they are now sequestered" so that they must be used for the intended purpose. Mr. Parmet also indicated that it was as important to quickly install spare parts as it was to have them available.

Mr. Stewart then stated that the Panel was informed about two weeks before that the repair turnaround time is getting worse at KSC and not better. He then stated:

> "The other thing they are concerned about... is apparently in the process of building a fourth Orbiter, the manufacturers and NASA are eyeing the existing spare parts as going into the fourth Orbiter. If that were to occur, then that would obviously exacerbate the spare part problem although it might accelerate the fourth Orbiter."

Testing and Certification

Mr. Nelson asked whether there should be more testing and verification of loads on the Orbiters? Mr. Stone expressed concern about increased loads on the Orbiter wings. He then stated:

> "Although the Orbiter itself is instrumented, there was never a real calibration test on the wing of the Orbiter itself. We have requested NASA to look into this. They agree with us but there hasn't been any budget set forth, so we don't see anything going forward... We don't think at the present time the loads are known that well. It takes a calibration with strain gauges and not with pressure gauges, as were used in the past... It should be done before first flight ..."

Mr. Nelson indicated that the Subcommittee would follow-up on this issue.

Mr. Stone later made the following suggestion:

> "We think that the first year's flights should be heavily instrumented to be monitored, so that information on structure, safety, reliability, performance and all those things can be gathered. It should be part of the certification program, so that they don't depend (only) upon the ground tests... We have suggested this. The NRC committee has suggested this, and I believe that is one of the things that NASA is going to do."

Utilization of Shuttle and ELVs

Mr. Nelson then asked the Panel members to elaborate on another conclusion in the ASAP Annual Report: "that the Shuttle should be used only where manned missions are deemed mandatory." The Panel members generally agreed with the need to emphasize greater use of ELVs for payloads particularly when costs to convert payloads from the Shuttle to ELVs are small. They indicated that a high launch reliability, comparable to that of the Shuttle, could be achieved for ELVs. They agreed that expensive payloads with man-tending requirements like the Hubble Space Telescope should be launched on the Shuttle and that many of the Space Station payloads could be flown on ELVs.

Mr. Nagle followed up by asking whether NASA was willing "to consider the ELV alternative and proper planning to utilize ELVs." Mr. Stewart indicated that NASA had a great stake in the Shuttle's use as the "Nations's launch vehicle." He went on to state:

> "They have resisted reintroduction of ELVs because they saw it striking at the heart of the whole rationale that initially launched the Shuttle... I think that is changing because I think that original rationale no longer is reasonable."

Mr. Stone indicated that the main problem at NASA preventing the greater use of ELVs was a budget problem -- how to acquire the necessary funds "given the realities of Gramm-Rudman" and other constraints.

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Oversight Responsibilities and Potential "Gridlock"

Mr. Nelson then asked the Panel to elaborate on the concern expressed in the testimony about "oversight gridlock." Mr. Stewart indicated that "it is the kind of statement that can be easily misunderstood." He went on to say:

> "...what your looking for is a kind of balance between what the line management have the responsibility for doing and the sense of self-confidence so they can do it successfully, and an appropriate level of review and audit and inspection that you obviously want to have in a program of this complexity. ...right now there is by and large a pretty good balance between the line management people at NASA, who in the end have got to have the support and self-confidence to make the tough judgments that are going to have to be made and the review groups... You can't permit review groups to kind of be a buffer for the kind of responsibility that rests ultimately with the Administrator."

Mr. Stewart agreed with a comment by Mr. Nagle that periodic outside review of an organization is needed to make sure that internal policies are good and that the organization doesn't become complacent. Mr. Stewart indicated that the ASAP had talked about a number of NASAs problems before the Challenger accident, but "did not do it with the kind of clarity and force that, in retrospect, we should have.

Mr. Nelson asked whether the Panel could "suggest to us anything that we can do to assure that there is not undue pressure to increase the flight rates in the future. Mr. Stewart responded:

> "What you can do Mr. Chairman, I think as a committee is to continue to look at the issue of how the Shuttle is serviced for reflight and the kind of procedures that are in place, the kind of discipline that is displayed in following those procedures, because that is where the ultimate safety factors get handled. As long as there is a pretty good consensus that we know what we're doing and we've got procedures set out, we're not working excess overtime rates -- the kind of evidence that was clearly there for all of us to see -- those are the sort of things that I think require occasional oversight by the committee..."

Congresswoman Connie Morella (R-MD) later followed up with a series of questions concerning how Congress might best carry out Shuttle program oversight responsibilities in the future. Mr. Stone indicated that the first flight was not the problem and that he was more concerned about what happens after 10 or more flights when the program settles into "a routine." Mr. Stone also indicated that Congress should look into such areas as turnaround time, and kind of procedures and discipline that are being followed as part of the annual oversight process. He stated that ASAP would continue to monitor the situation and "if something really alarms us, we will be ready to pass that on to the Administrator or the Congress..."

Mr. Nagle then indicated that he was puzzled by the fact that many recommendations of the Panel should have been anticipated and put in place years ago. Mr. Stewart responded:

"One of the great puzzles in government or in private life, is what makes some organizations successful and others not? It's obviously a lot of things. It's clear that organizational lines in NASA got all twisted around. Headquarters wasn't really leading the organization. The centers were really leading the organization, and in a very competitive way at times. The battle over turf, which we talk about, all of that was, I think, quite real.

When that happens, responsibility and authority is not clear, accountability is not clear, and discipline suffers. You get into a kind of downward spiral, and I think that is really what NASA gradually slipped into over time. It was not something that all of a sudden wasn't there. It was aided and also abetted by the pressure that NASA was under to meet a schedule that was essentially unmeetable, given the technology they had to work with.

When it was declared by the White House and by NASA at the end of the fourth flight that the Shuttle was now operational, that created a whole set of expectations which NASA then did their best to meet. They went out and they sold space on the Shuttle like they were selling soap. They had promotional campaigns, and they did all kinds of things, and they built themselves into, in a sense, an unwinnable situation. By selling space, they then had an obligation to deliver it to the customer. That meant an unrealistic flight schedule, and all of those things contributed to the breakdown of the organizational excellence that had been NASA's hallmark.

All of this suddenly became clear when the Challenger blew up, so now it is clear and people are going about to fix it. I think they are proceeding in a generally satisfactory way and encouraging way, but it is a very complicated operation. Why an organization gets off in that kind of a circumstance when there were still excellent people, and people who really cared, is a puzzling, difficult question. A lot to do with personal attitudes, work environment, sort of a political environment in which NASA operates -- all those things were contributing factors, it seems to me."

C. National Research Council Panel on Technical Evaluation of the Redesign of the Space Shuttle Solid Rocket Booster

Dr. H. Guyford Stever, Chairman, National Research Council Panel on Technical Evaluation of the Redesign of the Space Shuttle Solid Rocket Booster was accompanied by the Panel's Project Director, Dr. Myron F. Uman. The Panel is evaluating the technical aspects of the new designs as well as the testing and certification program. At the time of the testimony, three panel reports had been issued to the Administrator. Dr. Stever reviewed the current status of the SRB program in light of recommendations made by the Rogers Commission and the Committee's investigative report on the Challenger accident. Dr. Stever emphasized the following points in his written and oral testimony:

O "Because the (SRB redesign) program lacks concurrently developed alternatives for major components of the design, the redesign effort would be substantially extended if tests showed that any component of the baseline design is inadequate, with a loss of valuable time before safe and reliable Shuttle flights can resume."

  - O "The new case-field joint design selected by NASA appears to have eliminated the weaknesses of the earlier design that contributed to the accident. Tests of the new joint designs will have to be performed, however, before we can state with confidence that they are fully understood and verified. ...the redesign team should institute a practice of forecasting test results and establishing success criteria a priori to enhance confidence in its understanding." This practice is being introduced into the program.

- O Planned full-duration ground firings of motors should duplicate actual flight designs as closely as possible. "Neither vertical nor horizontal static firings can faithfully simulate the exact conditions of flight. However, provided that full-duration ground tests incorporate simulation of the important dynamic loads experienced at launch and during flight, horizontal testing should be appropriate." Two or more full-scale, full-duration, dynamic tests with simulated launch and flight loads should be completed before flight.

- O "New performance specifications that clarify the intended range of operating conditions, including temperature, have been written and are being implemented by the design team. ...The Panel has expressed concern that the separation of responsibilities for defining requirements and designing the booster may not be sufficient and that waivers from the requirements can be approved by persons with managerial responsibility for the design. Proposing waivers or revising specifications to match a particular design should be subject to the most careful scrutiny."

- O Not all conditions of flight can be tested on the ground. Verification of some design aspects can only occur with flight experience. NASA should "establish and maintain a strong directed program for continued evaluation and improvement in reliability after flights are resumed. ...In the longer term, completely new designs, possibly radically different from the current one, may be preferred to enhance safety or improve reliability, performance or cost-effectiveness. ...NASA should also vigorously pursue a program to develop the next and future generations of motors..."

- O The redesign team should "develop improved controls on supplied parts and materials" and those parts used in the testing program should be subject to the same quality control as qualification and flight motors. NASA has improved its understanding of critical processes and materials.

  - O Case growth phenomenon is better understood and can be taken into account empirically in the design and processing of the SRB segments. The issue of reuse of the segments can only be resolved after flights resume.

Response to Member's Questions

General Status of SRB Redesign Program

Mr. Nelson asked whether Dr. Stever was satisfied with the testing and certification of the redesigned SRB? Dr. Stever indicated the testing program was just beginning and he didn't know what the results would be. He thought there would be some surprises when full-scale, full-duration testing begins. He then made an interesting point concerning three criteria that must be met for any hardware to be successful over the long-term. First, the design must be forgiving. Second, the hardware must be manufactured properly. Third, the hardware must be assembled and operated properly. He later stated:

> "... 51-L failed for two of these reasons. It was misused and it had a non-forgiving design."

Mr. Nelson later asked whether there were additional SRB fixes that the Panel might recommend? Dr. Stever indicated the Panel had suggested a number of promising alternatives, which have slightly longer development times, in case problems occur in testing the baseline redesign.

SRB Joint Problems

Mr. Packard asked whether Shuttle parts other than the SRB joints containing O-rings are affected by low temperatures. Dr. Stever responded that he didn't believe other parts were significantly affected. Mr. Packard then asked whether it would be safe to launch under the conditions similar to what the Challenger faced, if the O-ring problems could be solved. Dr. Stever responded:

> "I think so. There are O-rings in the case-to-nozzle joint... but, there is a gas flow there that keeps it warmer than the case itself, so the case is most vulnerable... we recommended strongly in favor of finding O-ring materials that have a wider response rate, that is could cover the gap when the pressurization of the case took place, and to do it rapidly enough so that gas did not escape... the research program came up with some materials that have those capabilities, but they didn't work very well with the greases that are needed to prevent rust and deterioration... so NASA selected the heater ring in order not to wait until something was found that did work. The search, I believe, is still going on, but it is not a high pressure priority."

Mr. Packard then asked whether the new design would adequately resolve the problem experienced in the Challenger without a heater at the joint. Dr. Stever cited a number of other improvements in the joint design such as the "capture feature", but indicated that "temperature is still an important consideration" and that no-one would want to operate the current O-rings at low temperatures. He also indicated that more temperature measurements will be made close to the joint in the future rather than just ambient temperature measurements.

SRB Case Growth

Mr. Nelson asked whether the Panel had evaluated NASA's understanding of the case growth problem. Dr. Stever responded that a number of tests had been made and that NASA appears to better understand the problem. He went on to state:

> "It appears ...the case does grow in the first perhaps three pressurizations and then it ceases, and that's to be expected in the kind of metals they have. On the other hand, case growth is something that has to be watched all through the testing program, and the reuse of those things. But I do think that they have as good a surveillance of that (problem) as they can."

Future SRB Technology Advances

Mr. Volkmer asked whether a monolithic propellant grain SRB (i.e., a propellant grain with no gaps or seams) is still being discounted. Dr. Stever indicated that the proposed single propellant grain SRB still requires a segmented case with the case nozzle joint still being a particular problem. The Panel estimated that it would take considerably more time than the current redesign program to develop a monolithic SRB because a whole new pouring technology would be required. Dr. Stever indicated that he personally would like to see a monopropellant SRB developed some day.

Mr. Nelson then asked Dr. Stever to comment on NASA's proposal for an Advanced Solid Rocket Motor. Dr. Stever indicated that it was important to have a continuing long-term SRB development program. Some of the elements proposed for the ASRM might be brought into use long before the complete advanced motor itself would be ready.

D. National Research Council Panel on Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization

Dr. Edward E. David, Jr., Chairman of the National Research Council Panel on Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization was accompanied by Dr. Abe Silverstein, Consultant. The panel's objectives were to: (1) assess possible Space Shuttle flight rates using the most recent flight manifest as a baseline; (2) assess NASA's assumptions in the partitioning of payloads between the Shuttle and ELVs and whether these assumptions are reasonable; and (3) estimate cost trade-offs of a mixed fleet. The major findings of the panel are described in a recent report[9] and were summarized in the testimony as follows:

- "Three Orbiters can sustain a flight rate of 8 to 10 per year, with a surge rate of 12 per year for a limited time -- 3 to 4 months. For four Orbiters, the rate is 11 to 13 per year with a surge to 15." The estimates assume a 5-day, 3 shift per day, work week, an average mission duration of 7 days, 6 days for ferrying the Orbiter to the Kennedy Space Center with allowance for weather uncertainties, and periods of maintenance every few flights. The lower estimates are based on a turnaround time of 75 working days (21 work days/month) and the higher estimates assume a 60 working days turnaround time. The surge rates could be achieved for short periods of time and with stringent operational limitations such as standard payloads and short missions.

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O "These rates could be achieved following a transition phase of approximately 2 years after resumption of Shuttle operations..." The projected rates could be severely reduced by contingencies which would put one or more of the Orbiters out of operation for an extended period of time. Extended use of the Shuttle -- 15 to 20 years -- suggests possible need for replacement Orbiters at certain intervals of time. "The most critical assumption in estimating flight rates is that no Orbiter will be lost or become inoperable for a significant time."

O "Flight rates of 12 per year can be achieved only with augmentation of ground resources. Manpower at Johnson Space Center and spare parts production would have to be increased. Also, additional crew training facilities including software need to be procured..." The planned augmentation of the KSC ground facilities "appear adequate to handle such flight rates."

O "During launch and return passage through the atmosphere, "the Shuttle is stressed far nearer its design limits on every flight than is the case for transport aircraft and military aircraft except in wartime, for which such an occurrence is a rarity." The need for adequate Shuttle "safety reviews, logistics support, spare parts, extensive inspection and maintenance, and extreme care in every facet of the turnaround operation cannot be overemphasized."

O "The backlog of manifested payloads is expected to decrease as a result of delays and foregone windows of opportunity. The heaviest launch demand arises for the Space Station. A resolute NASA effort to procure ELVs is likely to be required to fulfill it space science program and commercial mandates." NASA's estimate that 22 of 130 backlogged Shuttle payloads could be moved to ELVs appears to be reasonable.

O "While the Air Force is procuring a number of Titan IV heavy launch vehicles and medium launch vehicles based on the Delta rocket (MLV), their early production seems likely to be devoted to Department of Defense payloads." "We understand that NASA has yet to implement a plan to procure ELVs." The availability of ELVs for other than DoD payloads is likely to be severely limited until at least the early 1990s. "Launch demand is likely to exceed supply for the foreseeable future." "NASA is putting sole reliance on the Shuttle for many years to come."

O Space Station launch demand would take most of the capacity of a 3 Orbiter fleet. The Strategic Defense Initiative (SDI) would need only 1 or 2 flights per year during the experimental phase with later phases likely to use the proposed heavy lift launch vehicle.

O "The total cost to the nation is relatively independent of the Shuttle/ELV mix." Costs depend primarily upon the size of the nation's space program. The total cost to put a given total weight into orbit over time is relatively independent of whether the Shuttle or ELVs are used.

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Response to Member's Questions

Shuttle Flight Costs

Mr. Skaggs asked whether the cost analysis mentioned in the Panel report also considered opportunity costs as far as the loss of launch windows for some of the payloads. Dr. David responded:

> "No, it does not include that, and I think it's a very good point that you make. ...We did not try to factor those costs in because they are very difficult costs to tabulate and to get reasonable estimates on. However, we were told by many of the commercial contractors who were waiting for launch, and by our space science colleagues, that it is much more important to have a timely launch... which is assured, than it is to worry about the last few dollars of launch cost, per se. In other words, that at least in the commercial area -- I suspect this is true also for the space science payloads -- the cost of launch itself is a small part of the total cost of the mission..."

Mr. Volkmer asked whether per-flight costs for the Shuttle would increase because of the future flight rates would be lower than had previously been planned? Dr. David stated that the Panel didn't look into the issue of per-flight costs, but, indicated (per-flight) costs are going to go up considerably, because fixed costs would have to be spread over fewer flights.

Shuttle Flight Rates

Mr. Nelson asked how one could account for the difference between the Panel's flight rate estimates and the higher NASA estimates? Dr. David stated he couldn't account for the differences in detail and that NASA did not strongly object to the Panel's estimates. He indicated that if NASA cannot meet its more ambitious goals, they will revert to using the lower flight rate estimates. He further suggested that it would be more prudent for NASA to utilize the lower estimates for planning purposes.

Utilization of Shuttle and ELVs

Congressman Robert Smith (R-NH) asked why NASA is not moving more quickly to use ELVs? Dr. David gave three reasons:

- O NASA has had a long-term focus on the Shuttle as the principal launch vehicle and it is difficult to change,
- O the additional costs of undertaking an ELV launch program may have made it difficult to obtain budget approval, and
- O the long-standing NASA belief that the Shuttle provides an opening to the future and an open ended capability.

Mr. Packard followed up by asking whether it would be preferable to have a mixed fleet and only three Orbiters or a fourth Orbiter and no ELVs. Dr. David stated:

> "A mixed fleet of ELVs and Shuttles is much preferable to a fourth Orbiter."

Mr. Smith followed by asking whether the Panel favored restricting the use of the Shuttle to payloads requiring man and to supplement the Shuttle with commercial ELVs? Dr. David indicated he favored that approach. He pointed out that ELVs fail more often than the Shuttle. Until ELVs are made more reliable, high-cost payloads may have to be flown on the Shuttle.

Mr. Nelson stated that it was the sentiment of the Committee to provide some funding for ELVs in the fiscal year 1988 NASA budget. Dr. David commented:

> "I'd like very much to see that. I believe it would please practically everyone in the user community. I might add, however, one caveat. In our report, we say that you have to look at the Shuttle as a fleet, which must be maintained and sustained over a period of years. Unless there is a good program of spare parts, (and) Shuttle building, which is scheduled on a reasonable and appropriate basis, the Shuttle fleet will be a declining asset and will eventually become unavailable to us. I think that is as important as seeing that we have the right mix of Shuttles and ELVs. In light of my answer to Mr. Packard, that I would prefer at the present time to see an ELV program to a fourth Orbiter, I would just add that caveat. I think you have to have both if you intend to use both. If you allow a transportation fleet to decline without a building program to replace the elements of it, you will not have it for very long."

E. NASA Advisory Council Panel on Issues of a Mixed Fleet

Major General Jasper Welch, USAF (ret.), Chairman, NASA Advisory Council Panel on Issues of a Mixed Fleet, testified on the findings and recommendations of the panel. The panel issued a final report[8] in March 1987, which addressed three problem areas: (1) What is an appropriate mix between the NASA's use of the Shuttle and ELVs?; (2) What are appropriate policies and practices for NASA in planning and providing launch services?; and (3) What role should NASA play with respect to current efforts to promote further commercialization of launch services? Some of the same issues and questions were addressed in a parallel study by the NASA Office of Space Flight (OSF) Mixed Fleet Study Team.

The panel endorsed most of the key conclusions and recommendations of the OSF study with some reservations related particularly to provisions for unscheduled delays in manifest planning. The panel's final report is included in the hearing record. The major points made by General Welch and the panel report were the following:

- O "The Shuttle must be recognized as a national resource of enormous importance to the U.S. space program. NASA policy should evolve from one that has maximized the use of the STS to a policy that preserves the Shuttle for those missions requiring its unique capabilities."

- O In transmitting the panel's report to the Administrator, Dan Fink, Chairman of the NASA Advisory Council, urgently recommended that "NASA begin immediately, through a request for a supplemental budget, to provide sufficient ELV launch capability or service to achieve the

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robustness required for an effective space program." A recent National Security Decision Directive (NSDD) "requires NASA to contract for launch services and not for the purchase of ELVs per se."

- "'Robustness,' the "sine qua non" of space transportation, is measured by the: (1) adequacy and sustainability of the launch rates; (2) capacity provided to accommodate uncertainties and unpredicted requirements; (3) ability to recover rapidly from stand-downs; and (4) capability to launch a diversity of spacecraft including large and heavy payloads. A successful program must be managed to meet each of these requirements."

- The panel does not agree that economics dictates that the Shuttle should be launched as often as possible to minimize per launch costs. "Rather, we place primary importance on the enormous cost of delays that are imposed on the (helpless) user community." ...The Task Force is immensely sobered by the enormous budgetary costs, opportunity costs, and program disruption of the current unplanned stand-down. ...This cost and disruption overshadows, in out view, the previous custom of evaluating launch services on a cost to orbit if everything works basis."

- The most important consideration is to plan for inevitable stand-downs. The duration and frequency of stand-downs are as important in establishing the overall launch rate as the independent launch rate in a period of no stand-downs. Resource expenditures must be balanced between activities aimed at achieving a high flight rate when there are no stand-downs and activities aimed at the prompt restoration of flights after unplanned stand-downs.

- In the past, the user community has had no voice in the policies that govern the establishment of their launch services. That is bad public policy. The Federal Government has a fiduciary responsibility because many of the space payloads are developed with Federal funding. The Federal Government should not impose additional costs on users because of inadequate planning for stand-downs. The users should also do a better job of stand-down contingency planning. The panel found that--even for complicated payloads--an alternate launch capability could be maintained up until a few months before launch for a small premium.

- "NASA planning should be based on a 'robust 12' Shuttle flights per year" from KSC assuming a 4-Orbiter fleet. However to achieve 12 flights per year, certain resource planning, e.g. logistics, should be based on 16 flights per year to provide adequate margins to protect against long stand-downs.

- Every effort should be made to off-load payloads from the Shuttle to ELVs. Even at 12 Shuttle launches per year, the launch capacity shortfall will continue through 1994. The shortfall remains in spite of (1) the termination of NASA's commercial launch activities, (2) the abandonment of 28 Shuttle equivalent space science and application payloads, (3) the delay of the remaining science and application payloads by an average of approximately 3 years, (4) the diversion of many DoD spacecraft to ELVs, and (5) the off-loading of all ELV compatible non-DoD payloads to ELVs.

- The long-term planning for the Space Station has not yet taken into account the realities of the space launch shortfall. The launch of Space Station hardware would present a golden opportunity for the expanded use of ELVs. A serious effort is required in 1987 by NASA to resolve the post 1994 launch shortfall problem.
- A Heavy-Lift Launch Vehicle (HLV) is needed to expedite the deployment of the Space Station, to enhance national security, and to demonstrate the U.S. commitment to a space program in general. The HLV should be jointly developed by NASA and the Air Force. A single joint program office could manage the development of two HLVs. The first would be Shuttle-derived for use in the near-term. The second would meet other criteria for use in the long-term.
- "The Secretary of Defense and the NASA Administrator should develop and sign a Memorandum of Understanding (MOU), which defines the relative roles, responsibilities and authorities of DoD and NASA elements in the development, procurement and management of common-use launch systems."
- "A study should be initiated to evaluate the constraints imposed by the current complement of launch pads and integration facilities on launch rate, surge capability, absorption of delays, and accelerated recovery from stand-downs. The study should provide recommended actions to substantially alleviate any identified limitations."
- "A study should be undertaken to evaluate the robustness of the upper stage vehicle fleet to exploit fully the diversified launcher family."

Response to Member's Questions

Utilization of ELVs

Mr. Packard asked Gen. Welch what might constitute a balanced optimum space program that would prevent long stand-downs? Gen. Welch indicated that different types of missions could tolerate stand-downs of different durations. For those missions that could not tolerate a long stand-down, alternative launch plans should be considered from the beginning of the payload development and planning process. He went on to state:

> "The current Shuttle delay is quite long for two exasperating reasons. First, there was not a lot of planning associated with thinking through what would happen if you had a stand-down. Second, we had run a very thin development program, and the alternatives to the (SRB) seals were not in an advanced development program... of the type Dr. Stever is recommending... I think the thing to do is basically to have two ways to go to space for every mission."

Mr. Packard followed up by asking: "Do you think that's doable?" Gen. Welch indicated that the Panel had found that one could maintain alternative

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launches for a small premium even for the most complicated payloads, up until just a few months before the scheduled launch.

Mr. Packard asked how much more it would cost to maintain a dual launch capability? General Welch said that no systematic budget estimates were available. He stated that such additional costs would be far less than the costs associated with unexpected stand-downs.

Mr. Packard asked whether the Space Station would require a dual launch program? Gen. Welch responded:

> "I would not advise going forward with a single launch program on the Space Station."

Mr. Nelson then asked whether Gen. Welch could provide any advice with regard to the acquisition of launch services rather than ELVs? Gen. Welch stated:

> "...whatever may be right in the long term, we wouldn't rock the boat in the short term... now is not the time for experimentation with regard to procurement policy."

Development of a Heavy-Lift Launch Vehicle

Mr. Nelson asked whether NASA should undertake the development of the Heavy-Lift Launch Vehicle to help launch the Space Station, whether the development should be a joint NASA-Air Force project, and whether such a vehicle should be Shuttle derived? Gen. Welch indicated he favored the development of the HLV via a joint program but couldn't choose between a Shuttle-derived or more advanced type of vehicle. He stated that a joint program office could manage the development of two vehicles, "one of which is near-term -- and I would use that term rather than Shuttle derived -- and one of which is long-term and meets other criteria."

III. REVIEW OF THE SHUTTLE RECOVERY PROGRAM

This section contains a review of the progress being made in the NASA Shuttle flight recovery program. The progress is evaluated primarily in terms of the recommendations made in the 1986 Challenger Accident Report[2] issued by the House Science, Space, and Technology Committee. For the most part, the findings, conclusions, and recommendations contained in the Committee's Challenger accident report were in agreement with those made in the report by the President's Commission on the Space Shuttle Challenger Accident.[1] However, the Committee went beyond the Rogers Commission in several of its recommendations as is described later in this section. A detailed summary of the conclusions and recommendations of the Committee investigation is contained on pages 3-33 of the Committee accident report. These recommendations are further summarized in the Appendix of this report. The major issues raised by the Committee report are summarized in this section together with the corresponding findings, conclusions, and recommendations of the oversight panels.

The major issues and recommendations raised by the Committee accident report can be categorized into the following six problem areas:

1. Program management, organizational, communication, and technical decision-making,
2. Safety, reliability, maintainability, and quality assurance,
3. Solid Rocket Booster design, manufacturing, and use,
4. Space Shuttle Main engine design and use,
5. Orbiter landing system design and use, and
6. Shuttle flight rate pressures and launch decision procedures.

Two other issues, which affect the Shuttle recovery program, have emerged subsequent to the Committee accident report and were discussed at the hearings. The additional issues are:

- The need to utilize expendable launch vehicles (ELVs) to meet future payload demand and reduce Shuttle flight rate pressures, and
- Excessive oversight of the Shuttle recovery program could cause program personnel to focus their efforts on responding to oversight requirements rather than meeting program requirements, which could lead to paralysis (i.e., "oversight gridlock").

Because the issue of the use of ELVs to supplement Shuttle launches is so closely related to the issue of Shuttle flight rate pressures, the former issue is discussed together with the issue of Shuttle flight rate pressures in Section III F. The issue of "oversight gridlock" is addressed together with management and organizational issues in Section IIIA.

The witnesses represented panels, which together have a mandate to review all of the safety-related aspects of the Space Shuttle recovery program including the use of expendable launch vehicles to complement the Shuttle for launching payloads.

The NASA Aerospace Safety Advisory Panel has a broad mandate to review safety, reliability, and quality assurance aspects of all NASA programs. The NRC Committee on Shuttle Criticality Review and Hazard Analysis Audit is primarily concerned with evaluating the Shuttle system certification and risk management procedures. The NRC Panel on Technical Evaluation of the Redesign of the Space Shuttle Solid Rocket Booster is concerned with the SRB redesign being carried out before Shuttle flights begin again and also long-term alternatives to further improve the safety and performance of the SRBs. The NRC Panel on Post-Challenger Assessment of Shuttle Flight Rates and Utilization, and the NASA Advisory Council Panel on Issues of a Mixed Fleet both addressed issues related to the large backlog of Shuttle payloads and the need to use ELVs to complement Shuttle payload launch capacity--critical issues related to reducing Shuttle flight rate pressures.

The testimony by representatives of the panels covered all of the major problem areas cited above except for issues related to the Orbiter landing system. However, the 1986 Aerospace Safety Advisory Panel Report[3], and the recent NASA response to the Committee accident report[4] addressed these issues so they will be covered in this section along with all of the other Shuttle recovery issues.

The remainder of this section addresses each of the major problem areas cited above. For each problem area, the related findings and recommendations of the Committee Challenger accident report are summarized, and then the progress that NASA is having in dealing with the problem area is reviewed.

A. Program Management, Organizational, Communication, and Technical Decision-making

1. Summary of Findings and Recommendations from the Committee Challenger Report

The Committee did not agree with the Rogers Commission conclusion that the underlying cause of the Challenger accident was poor communication or inadequate Shuttle program management procedures. Rather, the Committee believed that the fundamental problem was poor technical decision-making over a period of several years by top NASA and contractor personnel who failed to act decisively to solve the increasingly serious anomalies in the SRB joints. The Committee also believed that the existing NASA internal communication system was disseminating too much information, often with little or no discrimination in its importance. Accordingly, recipients had difficulty "separating the wheat from the chaff."

The Committee also expressed concern that NASA may not have had adequate technical and scientific expertise to conduct the Space Shuttle program properly. Staff reductions had occurred in key areas over the several years prior to the accident.

2. Review of Progress

Both the Rogers Commission and the Committee faulted the pre-accident NASA Shuttle program management structure because of its multiple and confusing reporting chains. Since the accident, extensive changes have been made in the Space Shuttle program management structure and in key program personnel. The changes have been aimed at strengthening the role of the NASA headquarters Shuttle program management staff, reducing inter-center conflict, improving communication throughout the Shuttle program, and improving Shuttle safety, reliability, and quality control programs.

Several witnesses commented that NASA has made considerable progress in resolving many of the management, organizational, communication and procedural problems that contributed to the Challenger accident. The extensive changes in personnel, organizational structure, and management controls should significantly improve the management and operation of the Space Shuttle program in the future. Whether these changes and improvements are sufficient to prevent another major accident in the future is still an open issue and one that is extremely difficult to evaluate. Accordingly, some concerns remain about NASA's technical decision-making capabilities and whether such capabilities have been sufficiently improved at all levels of the Shuttle program to prevent another disaster.

As directed by the Committee, NASA has reviewed the numbers and qualifications of key staff in technical and management positions. A new Office of Safety, Reliability, Maintainability, and Quality Assurance has also been created and the staff greatly strengthened in these areas. In its response to the Committee Challenger accident report, NASA has cited the extensive experience and college level technical training of the key technical managers at KSC, JSC, and MSFC. It can be noted that while formal technical education, extensive program experience, and on-the-job training programs are important and necessary for good technical decision-making, they will not be sufficient to ensure that correct technical decisions are made in the future. The attitudes, operating environment, and operational philosophies of key staff in the decision-making chain are as important as the technical competence and experience of the staff.

The Challenger accident occurred largely because of the failure of key decision-makers to recognize and correct the increasingly obvious problems associated with the SRB O-rings. In hindsight, the problem appears to have been more one of attitude rather than a lack of sufficient technical data. Additionally, it is not yet clear that this "attitude" problem has been completely solved in spite of all the positive changes that have been made. The Committee should continue to monitor the situation closely during the Shuttle recovery period and after Shuttle flights have resumed.

The Panels did not review the issue of the adequacy of NASA technical competence in depth, although the 1986 NASA Aerospace Safety Advisory Panel Report did discuss some related issues such as non-competitive Federal salaries and poor job security of contractor workers. General Slay did express some concern that NASA may not have access to sufficient competence in the area of statistical engineering. Statistical engineering is a critical discipline needed to support the application of probabilistic risk assessment techniques (see Section B, below).

Several of the witnesses expressed the view that an attitude of "safety first" and "schedule second" should be implemented and continuously reinforced during the life of the Shuttle program. This management philosophy should also be extended to other NASA manned programs in the future such as the Space Station. Further, the Associate Administrator for Safety, Reliability, Maintainability, and Quality Assurance should provide leadership in establishing new mechanisms and procedures to identify, evaluate, and resolve safety problems in all NASA programs.

Subsequent to the hearings, the Committee was informed that NASA plans to establish a new, confidential Shuttle safety reporting system. The system will enable employees to report safety problems to an outside contractor (Battelle Memorial Institute, Columbus, Ohio). If justified, the contractor will alert top NASA officials. The system is modeled after an existing Federal Aviation Administration reporting program for aviation safety problems.

Several of the witnesses also expressed concerns about the large number of groups outside of NASA, which are involved in reviewing and evaluating the progress being made in the Shuttle recovery program. There is a possibility that NASA officials might place excessive reliance on such groups to make critical decisions rather than to utilize such groups for advice and guidance. Several witnesses representing the Aerospace Safety Advisory Panel also cited the possibility of "oversight gridlock" occurring because of the large number of advisory panels, review committees, and Congressional committees involved in the Shuttle recovery oversight process.

While it is clear that too much oversight could cause additional burdens and stresses in the Shuttle program and be detrimental to its effective and safe operation, it does not appear that excessive oversight has occurred in the past or is now occurring. In fact, before the Challenger accident, there may have been too little oversight and attention paid to critical aspects of the Shuttle program by the Congress, high-level administration officials, and knowledgeable special interest groups.

It is difficult to determine the level of oversight that would be optimum for complex programs such as the Shuttle program. Once the Shuttle returns to routine flight status, the amount of oversight and number of oversight panels will be reduced. However, the Committee will continue its close monitoring of the Shuttle and other NASA programs to ensure that the lessons learned from the Challenger accident are not forgotten. The Committee should also continue to seek assistance from the NASA Aerospace Safety Advisory Panel, the Associate Administrator for Safety, Reliability, Maintainability, and Quality Assurance, and other experts to continuously monitor NASA programs. NASA program management officials should view such close scrutiny as an opportunity to better characterize and solve problems rather than as an unnecessary burden.

The Space Shuttle recovery program is clearly operating under an extremely demanding "success-oriented" strategy with the major goal of resuming safe and routine Space Shuttle flights as soon as possible. The program strategy assumes that each critical step of the recovery program--from problem identification, through component redesign, through testing and certification, through flight preparation and launch--will succeed (i.e., will produce the expected and planned results). The schedule is exceedingly tight with little or no time available to resolve unexpected problems, if they occur. Some witnesses expressed concern that insufficient attention has been given to assuring adequate flexibility in the recovery program in case serious problems occur. While it may be too late to change the basic success-oriented strategy that characterized the return to flight phase of the recovery effort, continuing routine operation of the Shuttle should incorporate a higher level of contingency planning to anticipate technical problems.

B. Safety, Reliability, Maintainability, and Quality Assurance

1. Summary of Findings and Recommendations from the Committee Challenger Report

The Committee's Challenger accident report concluded that the NASA SRM&QA programs were grossly inadequate and agreed with the Rogers Commission that a thorough review must be conducted on all Criticality 1 and 1R items and hazard analyses; a study should be conducted on Shuttle crew escape systems for use in controlled gliding flight; and NASA's Shuttle management structure, safety organization, communications procedures, and maintenance policies should be carefully scrutinized and improved. In addition the Committee recommended that NASA review its risk management activities to define a complete risk management program.

In addition to the problems with the Solid Rocket Booster (the direct cause of the accident), the Committee report also cited numerous other recurrent hardware problems, which were not fully understood or had not been corrected by NASA. Of particular concern were problems associated with the Space Shuttle Main Engines and the Landing System, which are addressed later in this report.

The Committee expressed a concern that NASA "does not yet understand how or why the deficiencies in Solid Rocket Motor testing and certification went undetected in spite of the very comprehensive processes and procedures used by the agency to conduct and oversee these activities." Without such an understanding, NASA will not be able to protect against a similar breakdown of the quality assurance and safety system in the future.

Another major problem identified by the Committee was that existing contract incentives used by NASA did not adequately address or promote safety and quality concerns--most emphasis was placed on meeting cost and schedule requirements.

2. Review Of Progress

The Committee Challenger accident report made more than 25 specific recommendations (summarized in the Appendix) related to different aspects of the Shuttle safety, reliability, maintainability, and quality assurance problems. NASA has made considerable progress in addressing most of these recommendations. Several problem areas still remain and are discussed in this section.

The Committee has noted that NASA has established a much stronger and comprehensive SRM&QA program. The fact that a new Associate Administrator position for SRM&QA has been established should assure high-level, continuous visibility and support for SRM&QA functions throughout the agency. Hundreds of SRM&QA specialists are also being hired to support program and line staff throughout the agency. The new Office of the Associate Administrator for SRM&QA has developed both short- and long-range plans for development and implementation of improved SRM&QA practices throughout the agency with particular near-term emphasis on the Shuttle program. While these improvements should enable more effective and uniform SRM&QA practices to be implemented throughout the agency, the ultimate effectiveness of such practices will depend on line and program managers and their staffs who are responsible for application of the SRM&QA practices to their day-to-day operations. As mentioned previously, program and line staff attitudes towards areas such as safety are as important as having good procedures and practices in place.

The Committee has also noted the progress that NASA has made in thoroughly reviewing and reevaluating critical Shuttle components and performing appropriate "Failure Modes and Effects Analyses" to better characterize potential safety problems with specific hardware. Numerous hardware fixes are being implemented in addition to those required to fix the SRB joint that was identified as the primary cause of the accident. Considerable work still needs to be done with regard to testing and certification of redesigned hardware.

The Committee expressed some concerns that NASA may not yet have paid enough attention to determining why the deficiencies in the pre-accident Solid Rocket Motor testing and certification went undetected. Such a "Lessons Learned" study would be important for the prevention of similar problems with other hardware in the future.

One important deficiency in the Shuttle recovery program not yet fully addressed by NASA was cited by both the NRC Panel on Shuttle Criticality Review and Hazard Analysis Audit and the Aerospace Safety Advisory Panel. The deficiency concerns the lack of progress being made by NASA in implementing a comprehensive Shuttle risk management program, which utilizes probabilistic risk assessment (PRA) techniques to evaluate relative risk or the relative importance of different courses of action. The Committee accident report also cited the need for NASA to utilize probabilistic risk assessment methods to evaluate safety problems with critical Shuttle components.

The panels emphasized that PRA methods should be used only to establish the relative probability of different accident scenarios occurring and for assigning relative priorities to critical items. PRA techniques should not be used to establish the absolute probability of a failure occurring. To-date, NASA has undertaken two pilot projects aimed at utilizing PRA techniques to evaluate the probability of failure of two critical Shuttle components--the Orbiter auxiliary power unit and the Shuttle main propulsion pressurization system. While such pilot projects will provide valuable, limited, direct experience with the application of PRA techniques to specific critical Shuttle hardware, some disappointment was expressed that a more comprehensive PRA program will not be in place before the next Shuttle flight.

The Aerospace Safety Advisory Panel expressed concern about the need to further evaluate and characterize structural loads and stress conditions on the Orbiter--particularly in the mid-fuselage area and portions of the wing. There is also a need to carry out a more thorough calibration of loads utilization strain gages before the next flight and for Shuttles to be instrumented to evaluate loads for at least the next several flights.

The Committee has noted the progress being made in improving Shuttle processing operations, but is awaiting a report from NASA on the findings and recommendations of the Shuttle Processing Review Group.

The problems of inadequate spare parts and unnecessary cannibalization appear to be less serious now than before the Challenger accident. However, the Aerospace Safety Advisory Panel expressed concern about the NASA's capabilities for replacing or repairing Line Replaceable Units (LRUs), assurance of configuration control and currency of engineering drawings, and the applicability of ground support equipment and test/checkout units. The NRC Committee on Shuttle Criticality Review and Hazard Analysis Audit also cited the need to better integrate different parts of the Shuttle processing system (e.g., engineering changes should be better integrated with the Failure Modes and Effects Analysis process). The testimony of these panels indicate that there still may be some Shuttle processing and maintenance problems. The Committee should continue to monitor this situation.

None of the panels explicitly addressed the issue of whether existing Shuttle contracts contain sufficient incentives for safety and quality. Although NASA has made an initial review of existing Shuttle contract safety and quality incentives and concluded that sufficient incentives do exist, the Committee has continued to express some concerns that existing contracts do not have sufficient incentives. The Committee should continue to monitor and evaluate this issue in the future.

The Committee is awaiting the findings and conclusions of the final report of the joint NASA/USAF team reviewing the Shuttle Range Safety System (RSS). The witness panels had not reviewed this issue as of the time of our hearings.

C. Solid Rocket Booster Design, Manufacturing, and Use

1. Summary of Findings and Recommendations from the Committee Challenger Report

Like the Rogers Commission, the Committee concluded that the direct cause of the Challenger accident was a failure in the aft field joint on the right Solid Rocket Motor. The Committee stated that the "failure of the joint was due to a faulty design and that neither NASA nor Thiokol fully understood the operation of the joint prior to the accident." "Further the joint test and certification programs were inadequate, and neither NASA nor Thiokol responded adequately to available warning signs that the joint design was defective."

The Committee also expressed concern that NASA does not yet understand how or why the deficiencies in the Solid Rocket Motor testing and certification went undetected in spite of the very comprehensive processes and procedures used by the agency to conduct and oversee these activities. Without such an understanding, NASA will not be able to protect against a similar breakdown in the future.

An additional concern was expressed about the safety of the filament wound case SRB that was under development. The Committee recommended that NASA should consider moving the heaviest Shuttle payloads to expendable launch vehicles so that there would be no need to use filament wound case motors.

2. Review of Progress

Because a failure in the Solid Rocket Booster aft field joint was determined to be the specific technical problem which caused the Challenger accident, considerable effort has been spent to redesign the joint and other critical SRB components and develop new specifications for their use. The National Research Council Panel on Technical Evaluation of the Redesign of the Space Shuttle Solid Rocket Booster has extensively reviewed the NASA SRB redesign program and the plans for testing, certification, and use of the new SRB. The NASA Aerospace Safety Advisory Panel has also reviewed NASA work in this area.

Testimony from representatives of both panels indicated that the newly redesigned aft field joint is a marked improvement over the original design. Joint rotation should be considerably reduced by the addition of the "capture feature." The addition of an additional O-ring together with an improved propellant/insulation interface configuration should reduce the possibility of "burn through" or "blow-by" problems at the joint such as was experienced by the original SRBs. The addition of a hearing unit to assure that the O-rings are maintained within specified operating temperatures together with more strict limits on ambient temperatures at launch should also result in greater margins of safety. Similar improvements are being made to other critical components of the SRB such as the nozzle-to-case joint, and nozzle. Newly developed techniques for nondestructive evaluation of the propellant in assembled Solid Rocket Boosters should also improve safety margins.

There was agreement that substantial progress has been made in redesigning critical SRB components. The panels also viewed the SRB testing and certification program to be extremely important and stated belief that data from the test program will be essential to making a final decision about the adequacy of the redesigned critical SRB components. A major concern of the expert panels was the lack of alternative designs being developed concurrently for the critical SRB components--particularly for the case-field and case-nozzle joints. If the test data should indicate that there are serious problems with the redesigned SRB components, NASA might have to then initiate the development of another major redesign effort, which could take several more years to complete. Further lengthy delays would cause major programmatic and political problems for the civilian space program.

NASA has apparently not been successful in identifying a new O-ring material with improved resiliency over a broader temperature range that will also be compatible with the grease used in the joints. Thus, it seems likely that the original O-ring material (a fluoro-elastomer rubber) will continue to be used in the near-term. Improved manufacturing controls for the O-rings and other critical components are being implemented. Clearly, O-ring issues will continue to be the center of attention during the testing and certification program and after flights resume. The Committee should continue to closely monitor this issue.

The NRC SRB Evaluation Panel has recommended that NASA utilize predictive testing procedures in the SRB test program and perform at least two full-duration, full-scale test firings of the redesigned SRB before the next flight. The Panel has also recommended that these tests should simulate, as closely as possible, all structural and thermal loads expected to be experienced during ignition, lift-off, and flight. Predictive testing procedures would require design engineers to quantitatively predict, a priori, the results of the test firing and to establish well-defined criteria for determining the success or failure of a test. In response to this recommendation, NASA adopted the procedure of predicting the outcome of each SRM test starting with the full scale test firing of the Solid Rocket Motor last August.

However, there is also the long-term need to supplement test data with data taken during flights. Improved flight data would require more extensive instrumentation of the SRBs and also the establishment of procedures that will enable the complete evaluation of data from one flight before a subsequent flight is made. The long-term testing and flight data evaluation program should be part of a strong directed program for continued improvement of the SRBs.

The issue of reuse of the Solid Rocket Motor cases is still an open one. The witnesses presented some evidence that the problem of case growth is better understood now than before the Challenger accident. However, there are apparently other problems with reuse of the cases that could result from the redesign of the field-joint. The complete evaluation of these problems and the issue of the viability of reusing the SRB cases must await data and information to be gained from examining hardware used in flights.

While the panels did not explicitly address the issue of future advances in booster rocket technology such as the proposed NASA Advanced Solid Rocket Motor (ASRM) program, a number of comments during the hearing supported the view that long-term research and development to improve booster performance and safety is essential. Such improvements could include the pursuit of new concepts such as pressure fed liquid boosters, hybrid liquid/solid propellant boosters and monolithic propellant solid rocket boosters. The Committee has reviewed NASA's program to undertake the development of an Advanced Solid Rocket Motor. In this, or any similar development efforts, the Committee has stated that improved safety should be no less important than improved performance. The critical issue to be addressed is whether theoretical safety improvements outweigh the safety benefits of a design of known performance with a long term history.

D. Space Shuttle Main Engine Design and Use

1. Summary of Findings and Recommendations from the Committee Challenger Report

The Committee Challenger accident report raised some serious questions about the relative safety of the Space Shuttle Main Engines--specifically, that the engines may have inadequate safety margins to ensure continued safe operation. Concern was expressed about the presence of persistent operating problems with the engines (e.g., cracked turbine blades, and defective hydraulic actuators and temperature sensors).

The Committee report stated that "NASA should give serious consideration to not allowing the Main Engine to be operated (except in emergency situations) at a thrust level greater than the standard 104 percent." The report also recommended that should NASA determine that higher engine thrust levels are needed for programmatic reasons, the agency should then take whatever actions are required to ensure that adequate operating margins are present to maintain safety.

2. Review of Progress

The Space Shuttle Main Engines (SSMEs) are a complex, high technology, system. The engines operate under extremely stressful conditions that are near the performance limits of their materials and components. Because the SSMEs are reused, a complex and stringent testing and certification program, and a comprehensive repair and maintenance program are required to assure adequate safety margins. Performance requirements for the SSMEs also have a significant potential effect on safety--particularly, the levels and duration of the maximum throttle levels used during flight. NASA has made considerable progress in evaluating, understanding, and fixing a variety of potential problems with the SSMEs. However, concerns continue to exist regarding potential safety problems associated with the design and operation of the SSMEs.

The NASA Aerospace Safety Advisory Panel (ASAP) did review the SSME program as part of its regular oversight process. In its testimony, the Panel stated that a number of significant problems associated with the SSMEs remain to be solved. These problems include: high-pressure turbopump blade cracks, high-pressure fuel turbopump coolant liner buckling, main combustion chamber coolant outlet neck cracks, and 4000 Hz vibrations in the thrust cone region. Such problems should be resolved before the resumption of routine Shuttle flights. The Committee will continue to closely monitor the progress being made on resolving such problems.

The ASAP agreed with previous recommendations of the Committee and plans by NASA to operate the SSMEs at a thrust level less than 109% until safety margins could be improved. The panel further recommended that the SSMEs should be constrained to operate at thrust levels of 104% or less, except under emergency conditions, and that it would be prudent to operate the engines at no more than a 100% thrust level until the Phase II engines have accumulated significant flight data.

The ASAP also expressed disappointment that progress on the development of an improved margin engine had gone very slowly because of limited funds and the lack of test stand availability.

E. Orbiter Landing System Design and Use

1. Summary of Findings and Recommendations from the Committee Challenger Report

The Committee Challenger accident report recommended a new system specification to overcome the inadequacies of the Orbiter landing gear, tire, wheel, brake, and nose wheel steering systems. The Committee also concluded that Orbiter landings appear to be high risk even under ideal conditions, which seldom occur.

2. Review of Progress

The Committee Challenger accident report made a number of recommendations aimed at improving the design and use of the Orbiter landing system. The testimony of the witnesses representing the different Shuttle recovery program oversight panels did not include comments on the progress being made to resolve the landing system problems. However, landing system problems have been a concern of the NASA Aerospace Safety Advisory Panel since 1981. The 1986 ASAP Annual Report[5] does describe a number of actions being undertaken by NASA to improve the operation, testing, and design of the Orbiter landing system. The NASA response to the Committee challenger accident report[6] also reviews the progress in this area through February 1987.

These reports indicate that NASA is addressing most of the recommendations of the Committee, which are related to the design of the landing system. The National Space Transportation System Landing Safety Panel is formally documenting an overall description of the Orbiter landing system. All of the hardware has been reevaluated with regard to safety and performance requirements and a number of modifications will be made before the next flight. Changes are also being made to brake testing procedures including vendor acceptance tests.

A number of modifications are being made to the hardware to improve safety margins. A thick-stator beryllium brake will be used on the next flight, which is expected to provide 65 million foot-pounds of energy absorbing capability. For the longer-term, a new structural carbon brake will provide capability well in excess of the modified beryllium brake. Critical certification tests for the structural carbon brake were scheduled for mid- to late-1988.

Progress is also being made in meeting the Committee recommendations that relate to the use of the landing system. For example, the nosewheel steering system is being modified to provide additional safety margins. Tire and runway surfaces are also being studied with the objective of reducing potential tire failures during landing.

In addition, NASA is actively considering the purchase of an additional 747 aircraft that can be modified to carry the Space Shuttle Orbiter in order to remove the existing Shuttle Carrier Aircraft as a single point of failure whose unavailability could ground the Space Shuttle for an extended period of time.

NASA has examined the mission planning process with a view towards minimizing the need for abort site landings. However, payload and trajectory requirements will normally result in the possible need for a transatlantic abort site landing. New requirements are being developed to reduce risks at abort site landings.

NASA is also evaluating the astronaut flight landing training program with the objective of improving and expanding facilities and procedures. Additionally, NASA is considering the conversion of an existing aircraft to be a fourth Shuttle training aircraft.

A Space Shuttle Weather Forecasting Advisory Panel has been established to review existing weather support capabilities and plans and to recommend improvements for the Shuttle program. The panel includes a representative from NOAA, as well as the U.S. Air Force, and the National Center for Atmospheric Research. Various weather forecasting system improvements are being reviewed, the statistical weather data base for all Shuttle landing sites has been revalidated, and minimum weather measuring equipment requirements have been established for both end of mission and abort sites. NASA has also requested the National Academy of Sciences to identify concepts for instrumenting the Kennedy Space Center with a prototype "now-casting" facility capable of 90 minute high-confidence level forecasts.

F. Shuttle Flight Rate Pressures and Launch Decision Procedures - The Use of Expendable Launch Vehicles

1. Summary of Findings and Recommendations from the Committee Challenger Report

The Committee Challenger accident report found that NASA's drive to achieve a launch schedule of 24 flights per year created pressure throughout the agency that directly contributed to unsafe launch operations. The report also stated that the pressure to push for an unrealistic number of flights continues to exist in some sectors of NASA and jeopardizes the promotion of a "safety first" attitude throughout the Shuttle program.

The report went on to state that the Committee, the Congress, and the Administration played a contributing role in creating this pressure. At the time, Congressional and Administration policy and posture indicated that a reliable flight schedule with internationally competitive flight costs was a near-term objective.

Pressures within NASA in attempting to evolve from an R&D agency into a quasicompetitive business operation also caused a realignment of priorities in the direction of productivity at the cost of safety. The report emphasized that NASA management and the Congress must remember the lessons learned from the Challenger accident and never again set unreasonable goals which stress the system beyond safe operating levels.

The report also recommended that, in order to reduce the pressure on Shuttle launch operations in the future, NASA management should improve mission planning and Shuttle preparation procedures, ensure efficient use of resources, and not impose a flight rate on the system that cannot be easily sustained by those resources and the technical limitations of the Shuttle system.

2. Review of Progress

The issue of excessive pressures on NASA due to an attempt to meet unreasonable Shuttle flight rate goals is still an open one. On the one hand, the removal of non-Shuttle dependent commercial payloads and many DOD satellites from the Shuttle manifest will help to remove pressure on the Shuttle program. On the other hand, there are some factors that indicate that flight rate pressure could continue to be a problem in the Shuttle program. These factors include NASA launch rate projections that one panel of experts believes to be unrealistically high; slow progress by NASA in procuring either expendable launch vehicles or expendable launch vehicle services; and the continuing desire of NASA, against the advice of several key panels, to use the Space Shuttle for missions that do not require either the presence of man or the unique capabilities of the Shuttle.

One key area of uncertainty is the likely Shuttle launch rate that can be sustained by NASA over the long-term. The NRC Panel on Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization closely examined the Shuttle flight rates that could be attained by NASA for both a 3-Orbiter and a 4-Orbiter fleet. The Panel's estimates for both sustained and surge flight rates were generally 25% lower than NASA estimates. The actual flight rates will be determined only after Shuttle operations begin again. However, the general consensus was clearly that NASA must begin to take immediate steps to assure the "robustness" of the Nation's access to space including rapid procurement of ELVs and/or commercial launch services. The statements of Members and witnesses clearly indicated that it is crucial for NASA to move quickly towards greater use of ELVs.

Two weeks after the hearings, the NASA Administrator, Dr. James C. Fletcher announced a plan to acquire ELV services for NASA missions. In making the announcement Dr. Fletcher stated: "NASA's purpose in seeking expendable launch series is to lessen dependence on a single launch system, the Space Shuttle. . ." "A major objective of the plan is to accelerate the deployment of the nation's backlog of space science missions." The reintroduction of expendable launch vehicles will provide NASA with a so-called "mixed fleet" and help achieve this objective. The plan to implement a mixed fleet strategy will lead to significantly greater payload launch flexibility in the future and should greatly help to reduce Shuttle launch pressure. Though NASA has announced a decision to implement a mixed fleet strategy, there is lingering concern that the agency may not be moving fast enough to implement this policy.

It can also be noted that there appears to be a difference in NASA planning for Space Shuttle utilization versus the view of some key advisory panels. For example, at the hearings, representatives of the Aerospace Safety Advisory Panel, the National Research Council, and the NASA Advisory Council all expressed the view that the Shuttle should be preserved for missions that either require the presence of man or the unique characteristics of the Orbiter--while all other missions should be conducted by expendable launch vehicles. Some actions by NASA officials (e.g., manifesting 1990 and 1992 launches of Tracking and Data Relay Satellites on the Space Shuttle rather than on expendable launch vehicles) seem to indicate that the Agency does not fully concur with this philosophy.

Two of the witnesses made an important series of points regarding the cost of using the Shuttle and/or ELV's. Dr. David pointed out that the total cost to the Nation is relatively independent of the Shuttle/ELV mix. General Welch also made the point that economics does not dictate that the Shuttle should be launched as often as possible to minimize per launch costs. He further stated that the cost of unplanned Shuttle stand-downs overshadows the previous custom of evaluating launch services on a "cost-to-orbit-if-everything-works" basis. These statements represent a major change in the way of viewing Shuttle economics. These views are worthy of a considerable amount of attention.

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APPENDIX

SUMMARY OF RECOMMENDATIONS IN THE COMMITTEE'S CHALLENGER ACCIDENT REPORT

A. Recommendations Related to Program Management, Organization, Communication, and Technical Decision-Making

Safety First - Launch Schedule Second

- The Committee recognizes the national need to return the Shuttle to flight status as soon as reasonably possible. As noted in NASA's July 14, 1987 report to the President, safety will determine the launch schedule. However, NASA should consider the proposed launch date of early 1988 as a flexible one which should be slipped further if necessary. The Shuttle should not be launched again until NASA can assure that safety criteria have been met.

Management Structure

- NASA should structure the Shuttle Program management to define clear lines of authority and responsibilities. This restructuring should take into account the special role each center must play and be especially sensitive to the need for cooperation and support of all the participants to achieve a common goal. NASA should give special consideration to moving the Program Manager to NASA Headquarters to avoid the confusion and inter-center rivalry that resulted from having a large multi-center program managed out of one of the participating centers.

Communication

- NASA management should review the process of providing information on significant actions so that awareness by concerned managers is assured.

Launch Decision-Making and Change Control Process

- NASA must reconsider its efforts to categorize the Shuttle as an operational transportation system.

- NASA should review the launch commit criteria procedures, especially those for dealing with violations, to lessen the reliance on engineering judgement under stress.

- NASA should make every reasonable effort to record meetings where key decisions might be made; in particular, all formal Flight Readiness Reviews, including the L-1 and the mission management team meeting should be recorded, where feasible by video.

- NASA should establish rigorous procedures for identifying and documenting launch constraints. The individuals responsible for implementing this procedure should be clearly identified, and well-defined and understood criteria for waiving them should be established.

- It is important that a clear delineation of responsibilities for the separate SR&QA disciplines be documented. It is also essential that the relative importance of each of the three separate disciplines be established as an integral part of the Space Shuttle program. These functions are the responsibility of NASA headquarters.

- The Associate Administrator for Safety, Reliability and Quality Assurance (SR&QA) should provide to the Committee, the agency's draft plan delineating the organization, goals, implementation strategies and resource requirements of the Office of SR&QA.
- NASA must carefully review the staff and resources devoted to the SR&QA function within NASA and contractor organizations for adequacy. The Administrator shall report to the Committee with his findings and recommendations.

Testing and Certification

- NASA should devote more attention to determining why the deficiencies in solid rocket motor testing and certification went undetected, so that appropriate action can be taken to uncover latent problems in existing hardware and to prevent similar problems in future development programs.
- NASA and its contractors should thoroughly reassess the adequacy of all testing and certification that has been conducted to date on each element of Space Shuttle flight hardware. Where deficiencies are found, they must be corrected.
- The independent review contractors participating in the hardware recertification plan should utilize sufficient specific technical expertise to insure adequate recertification of all elements of the Space Shuttle.

Risk Management and Use of Analytical Risk Assessment Methods

- NASA should develop and provide to the Committee a description of an overall risk management program as it relates to the Space Shuttle. This effort should include a determination of whether or not a more centralized coordination of a risk management program and issuance of direct risk management guidance directives are needed.
- NASA should review analytical methods utilized in the performance of risk assessment, including statistical analyses, trend analyses and probabilistic risk assessment methodologies to determine their applicability to the Space Shuttle program. Assistance from the National Academy of Sciences, or other appropriate organizations with expertise in these matters, may be required to adequately perform this review.
- NASA should review its certification testing to ensure that all critical items are adequately tested. Data obtained from these tests should be used when appropriate in conducting a formal risk assessment.
- NASA should exercise extreme caution in waiving launch constraints before correcting the problem that led to the launch constraint. The rationale should be based on rigorous scientific/engineering analyses or tests and should be understood and accepted by the program manager.
- When situations arise where "real-time" judgments are unavoidable, NASA should adopt a more conservative approach to waiving previously established

criteria. In no case should a criterion be waived without a thorough understanding of the rationale for the establishment of the criterion.

- O The Configuration Management System designed to control such changes (as those made in the flight production process and the manifest) must be reexamined by NASA as to its effectiveness in assuring that all hardware changes take place in a safe and reliable fashion.
- O NASA should review its change control process to determine the usefulness of differentiating between minor changes and significant changes.
- O Principal contractors should be required to make a clear, unambiguous statement concerning launch readiness just prior to launch.

Technical Expertise of Personnel

- O NASA should review the numbers and qualifications of key staff in technical and management positions and should consider additional training and recruitment of individuals to further the quality and safety of NASA's missions.

B. Recommendations Related to Safety, Reliability, Maintainability, and Quality Assurance

SR&QA Program Management

- O NASA should establish and maintain a strong and effective SR&QA program. Continuing support for such a program must come directly from the Administrator.
- O Although it is appropriate to establish strong contractor capabilities in the areas of SR&QA, the internal oversight responsibilities and coordination of SR&QA tasks must be the responsibility of NASA itself. In order to assure that the appropriate interfaces among the various subsystem elements that comprise the Space Shuttle program are maintained, a sufficient complement of NASA SR&QA management and support staff must be available to perform the necessary oversight and coordination tasks.
- O It should be the responsibility of the new Associate Administrator for SR&QA to fully specify the roles of safety and reliability engineering as well as quality assurance personnel within the Space Shuttle program, so that all critical aspects of the program and decisions related to the adequacy of hardware and subsystem performance are fully reviewed by these disciplines.

Hardware Fixes

- O NASA should ensure that, as part of its current review of Space Shuttle safety, it identifies, thoroughly evaluates, and then takes appropriate action on all serious engineering concerns raised regarding mission critical elements of Space Shuttle flight hardware.
- O NASA should ensure that before reinstituting Space Shuttle flight operations, it fully understands and has corrected all instances of serious in-flight anomalous behavior or failures involving mission critical pieces of hardware.

O The Committee requests that the new Office of Safety, Reliability and Quality Assurance conduct an independent assessment of the SRB field joint redesign efforts. In addition, the new office should also be integrally involved in reviewing all other critical component redesign efforts and NASA's recertification plan.

Shuttle Processing and Maintenance

O Because of the serious quality and safety concerns surrounding the contract, NASA should conduct a careful review of Shuttle processing, the SPC contract, and the relationship of flight hardware contractors and report its findings, recommendations, and proposed contract modifications to the Committee. NASA's reexamination should include a comparison of efficiency and safety under the SPC versus efficiency and safety during pre-1983 Shuttle processing operations, which heavily involved the developmental contractors.

O The Committee recommends that NASA provide its re-invigorated safety office with the authority to enforce scheduling that leads to safe overtime rates.

Spare Parts and Cannibalization

O NASA should examine the issues of spares availability and cannibalization and provide the Congress with a management and budgetary plan for correcting previous logistical problems.

O NASA should stop routine cannibalization and develop guidelines (including appropriate control and review procedures and roles for the SR&QA office) governing permissible cannibalization.

O NASA, in conjunction with the appropriate contractor, should consider designing and conducting an ET (external tank) liquid hydrogen leak/burn test to determine if corrective actions should be taken before the next Shuttle flight.

Hardware Manufacturing

O NASA should require the manufacture of critical items, such as the (SRB) O-rings, to be designated "critical" processes. Contractors should formally notify their employees involved in critical manufacturing processes of the serious nature of particular production processes.

O NASA should conduct a thorough review to ensure that all manufacturing processes involving Criticality 1 and 1R hardware components of prime and secondary contractors are appropriately designated "critical" processes.

Shuttle Contract Safety Incentives

O NASA should examine all Shuttle contracts and report to the Committee with its findings and recommendations on whether more incentives for safety and quality can be built into these contracts. This report should address, *inter alia*, the SRB production contract and the SPC.

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O NASA's new Office of SR&QA should be involved in the procurement and award fee processes, both to establish reasonable guidelines and rewards in new contracts and to judge performance of ongoing contracts.

Crew Escape System

O NASA should continue to respond to the recommendations of the Rogers Commission regarding (i) crew escape during controlled gliding flight and (ii) increasing the possibility of successful emergency runway landings. NASA should reexamine all crew survival options and report to the Committee on its findings.

Range Safety

O The Committee believes the administrator should prepare and submit to the Committee a comprehensive review of RSS (Range Safety System) requirements.

C. Recommendations Related to Solid Rocket Booster Design, Manufacturing, and Use

Redesign of Joints

O NASA should write and issue a new and more accurate performance specification which would cover the full range of thermal and structural requirements for the Solid Rocket Motors, with an adequate factor of safety for unusually low temperatures.

O The Committee concurs with the Rogers Commission Report Recommendations on new joint design, but believes it is more appropriate to be more explicit in identifying the weaknesses in the joint design that need correction.

O The field joints of the Solid Rocket Motors should be redesigned to account for the following features while providing a significant factor of safety:

a. Movement in the joint,
b. Proper spacing between tang and clevis,
c. Seals made to withstand high and low temperatures under all dynamic thermal and structural loadings,
d. Adequate sealing without the use of putty,
e. Protection against insulation debonding and propellant cracking.

O-Rings

O NASA should review its O-ring repair policy and contractor repair practices in terms of their effects on O-ring performance and safety. Such review should be completed prior to the resumption of Shuttle flights if, as anticipated, the new SRB joint design uses O-rings.

SRB Case Growth and Reuse

O NASA and the appropriate contractor should resolve through analysis and testing prior to the next Shuttle flight the cause of SRM case size growth and its impact upon booster and Shuttle performance, reliability of refurbished SRM case segments, and safety.

Testing and Certification

- In establishing a test program to certify the new Solid Rocket Motor design, NASA should consider the feasibility of including in combination and in the proper sequence all of the thermal and structural loads expected to be experienced by the Solid Rocket Motor during ignition, lift-off, and flight.
- NASA should consider reinstating full X-ray inspection of the propellant and insulation for all motors used on succeeding flights until new, more accurate inspection methods can be developed and implemented and there is unquestionable confidence in the SRM production process.
- NASA, in conjunction with the appropriate contractors, should investigate the development of new, more accurate inspection techniques which can detect "kissing voids" and other potential defects that cannot be detected by X-ray inspection.

Filament Wound Cases

- NASA should give special attention to both the cost and risks of using filament wound case Solid Rocket Boosters for very heavy Space Shuttle payloads versus the cost and programmatic impacts of simply transferring those payloads to expendable launch vehicles.

D. Recommendations Related to Space Shuttle Main Engine Design and Use

SSME Development Program

- NASA should continue its active development program for the Space Shuttle Main Engine. The program should be focused more on increasing operating margins.

Maximum Throttle Levels

- Because of safety concerns raised by knowledgeable officials, NASA should give serious consideration to restricting use of the 109 percent engine throttle setting to emergency situations only. If NASA decides that it needs to use the 109 percent throttle setting for other than emergency situations, the space agency should take whatever actions are required to ensure that adequate margins are present to maintain safety.

Testing and Certification

- NASA should closely scrutinize each of the concerns raised by Dr. Feynman regarding the agency's "fleet leader" concept for certifying Space Shuttle Main Engine components. The agency should also closely reassess its practice of selectively violating its "2X" rule for some main engine flight hardware elements.
- The Committee concurs with the Development and Production Team (of the Rogers Commission) conclusion that overtesting, limits testing, and

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malfunction-testing in the SSME program should be reemphasized to demonstrate full engine capability.

O NASA should prepare and submit to the Committee a cost benefit analysis of testing a SSME to destruction including: (a) utilizing additional SSME test stands; (b) utilizing additional hardware for the ground test program; and (c) the value of such a test.

O A vigorous study of fracture behavior should be conducted to minimize the hazard of cracked SSME blades and to increase the reliability and safety margin of blades. New blades and/or new policies for duration of blade use should be incorporated prior to the next Shuttle launch.

E. Recommendations Related to Orbiter Landing System Design and Use

Landing System Redesign

O The Committee recommends that NASA:

1. Assemble all of the fragmented studies, analyses, and conclusions on landing gear problems and integrate them into one engineering description of the system as it is now intended to be used. This should include consideration of the basic strength of the struts themselves and their attachments.

2. Write a new system specification and match the proposed design improvements to an acceptable reliability and certification specification.

3. Design a test and certification program adequate to meet criteria to fly and to continue well into future operations until understanding and confidence in the landing gear system is attained.

4. In anticipation of requirements for a new brake specification, accelerate a program to provide:

   Increased brake mass and/or heat sink,

   Substantial increase in energy absorption,

   Evaluation which weighs the experimental nature of the proposed 65 million foot pound carbon brake and its impact on the system against the penalty of weight of known materials (e.g. steel) for operational confidence.

5. Write updated subsystem specifications to upgrade the landing gear system to acceptable levels of performance to respond to the Rogers Commission recommendations.

Landing System Use

O The first priority to achieve an acceptable degree of landing safety and to have a sensible base to work from for improvement is to implement the recommendations of the Rogers Commission and the Committee on the landing gear system improvements to attain an operational capability. Then:

Instrument the system, and schedule all landings at Edwards runway for systematic concurrent testing until the landing gear system is understood.

Write a clean sheet set of rules based on results.

Determine the risk of accident with the B-747 Shuttle carrier aircraft (SCA) and its impact on the Shuttle program.

Extend every reasonable effort to assure a mission planning process to minimize the need for abort site landings.

Reevaluate and determine the degree of risk acceptable at abort site landings and bring abort site capability up to meet that risk level.

Expand astronaut matched team flight landing practice to cover all known exigencies. Propose additional training craft if necessary.

Join in a venture with NOAA to invent new technologies and techniques to learn new ways to understand the dynamics of Cape Kennedy weather phenomena to supplant the current inadequacy to forecast two hours ahead.

F. Recommendations Related to Shuttle Flight Rate Pressures and Launch Decision Procedures

Shuttle Flight Rate

O NASA must not attempt to achieve a flight rate beyond that which (1) can be supported by the budget and staff resources available; and (2) is consistent with the technical maturity of the Shuttle and the flexibility desired and needed in scheduling payloads. Management should ensure efficient use of resources but should not impose a flight rate on the system.

Mission Planning and Preparation

O The new Associate Administrator for Safety, Reliability and Quality Assurance must assure that any pressures to increase the Shuttle flight rate do not adversely influence mission preparation. The Associate Administrator must have the authority not only to stop a particular flight, (e.g., at a Flight Readiness Review) but to stop the whole mission planning process if necessary.

O Where appropriate, NASA should take steps to make the mission planning process standard and routine to reduce the time and resources needed to plan a mission. Before requesting more resources for the existing mission planning process (manpower, facilities, equipment), NASA should identify ways to improve the process.

References

1. Report of the Presidential Commission on the Space Shuttle Challenger Accident, Vols. I-IV, June 6, 1986.

2. Investigation of the Challenger Accident, Report of the Committee on Science and Technology, U.S. House of Representatives, Nintey-Ninth Congress, House Report 99-1016, Union Calendar No. 600, October 29, 1986.

3. Actions to Implement the Recommendations of the Presidential Commission on the Space Shuttle Accident, National Aeronautics and Space Administration, July 14, 1986.

4. Response to the Recommendations of the House of Representatives Committee on Science and Technology Report of the Investigation of the Challenger Accident, National Aeronatuics and Space Administration, February 15, 1987.

5. Aerospace Safety Advisory Panel Annual Report for 1986, National Aeronautics and Space Administration, February 1987.

6. Lessons Learned, An Experience Data Base for Space Design, Test, and Flight Operations, Gilbert L. Roth, Staff Director, Aerospace Safety Advisory Panel, National Aeronautics and Space Administration, November 1986.

7. Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization, National Research Council, October 1986.

8. Report of the Task Force on Issues of a Mixed Fleet, NASA Advisory Council, National Aeronautics and Space Administration, March 1987.

REVIEW OF THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION'S SPACE AND GROUND NETWORKS, AND COMMUNICATIONS AND DATA SYSTEMS

STAFF REPORT*

January 1989

* Dr. Paul Brower, Congressional Fellow
Subcommittee on Space Science and Applications
Committee on Science, Space, and Technology
U.S. House of Representatives
Washington, D.C. 20515

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I. EXECUTIVE SUMMARY

The purpose of this study is to review the programs of the National Aeronautics and Space Administration (NASA) intended to ensure the effective and efficient flow of data from a mission in orbit through processing and transmission to the user/researcher. The results are intended to provide a background and summary information about activities and challenges in the area of space science data communications and processing.

Following a review of NASA's space science data program evolution, four major issues are discussed. The issues and a brief summary follows:

1. Are future data flow projections realistic? If so, are the data requirements reasonable?

Review of NASA's scheduled and proposed missions indicates that projected space data traffic for 1995, at a minimum, will increase over 200 times that experienced and processed in 1985. Much larger data rates are possible; however, both NASA and non-NASA personnel interviewed believe that some of the larger data forecasts are not realistic nor reasonable. Both communities indicate that increased scientific user involvement with NASA is desirable to review data requirements and ensure that requested data is needed.

To meet the projected space science data flow, NASA has undertaken efforts to develop both distributed and centralized processing computer facilities. These generally have the support of the scientific community. NASA's Office of Space Science and Applications (OSSA) is attempting to satisfy earlier criticisms regarding coordination within NASA and the scientific community.

2. Can the scientific community analyze the flow of data envisioned?

According to scientists interviewed, a primary factor in determining if the projected increase in data can be analyzed depends on increased processing capability to format and prepare the space data for the researchers.

NASA has outlined several efforts that are underway to make the flow of data more efficient for researchers. The use of new data storage media may offer benefits and reduce the possibility of loosing archived data through deterioration.

On-line access to data and large supercomputing capability may further help scientists to analyze space science data. Also, NASA efforts on cataloging data, providing a browse capability for users, refurbishing archived data, and providing more on-line storage capacity is planned.

3. Is projected funding for science data handling adequate to provide timely data to researchers?

Cost projections for future space data handling by both the Congressional Budget Office and NASA were reviewed. Both sets of data reflected very gradual increases for future activities. Although there are new efficiencies being added, non-NASA sources question whether there may not need to be greater increases, although not directly in proportion to the increase in data rates, namely over 200 times.

Likewise, although efforts are underway to address the problems with space data archives (stored data), it is likely that more resources will be required.

Finally, many scientists indicated that funding for data processing and analysis should be separated from the mission operations budget. Separated funding would ensure resources for completing data analysis, would force better estimation of data analysis costs by both NASA and scientists, and might avoid end of project shortfalls that researchers maintain hampers proper archiving of analyzed data.

4. Is the second TDRSS (Tracking and Data Relay Satellite System) ground terminal (STGT) needed? Will a third terminal be required later?

NASA has projected that for communications between earth orbital missions and the ground, the TDRSS program will require a second ground station. Furthermore, NASA has concluded that the three mile distance between the stations is sufficient to avoid both stations going off the air due to thunderstorms. Also, NASA officials indicated that the 3 mile proximity will allow the TDRSS program to save personnel costs which contribute to a total estimated savings over ten years of $75 million.

Likewise, NASA maintains that the installation of a second TDRSS ground station and complete replacement of outdated computer equipment in the existing ground station will provide communications capability for NASA to eventually place four active TDRS craft into operation.

Finally, NASA officials contend that a third ground station will not be required to support the program as it proceeds with the planning for the next generation of relay satellites for the years 2000 and beyond. They believe the added redundant equipment in the ground stations will supply the capacity, even with contingencies, to meet space data flow requirements.

In summary, NASA's efforts to implement recommendations from CODMAC (the Committee on Data Management and Computation), the National Academy of Science, and others are starting to improve the availability of space data to scientists. However, some members of the scientific community feel that increased funding will be needed to make these efforts a success.

II. INTRODUCTION

Just as stars of a play are recognized while supporting cast members go unnoticed, the same may be for NASA's well publicized missions as compared to the underlying foundation of activities that make missions successful. In that regard, the communications and processing capabilities embodied in NASA's space and ground networks are key elements that can affect all of the agency's activities in space. These systems receive, store, transmit and forward a broad range of information including data, tracking, telemetry, commands, and other communications vital to successful missions. Moreover, the data processing provides information to the users as well as archived data for future researchers.

NASA has attempted to evolve these activities to satisfy growing data requirements. As early as October 1979, NASA officials stated, for the record, they recognized the need to further evaluate certain aspects of data management and to determine how support might be made better over the next decade. Their testimony can be summarized as follows: "The data processing aspect of our business has increased considerably in the past few years and with the advent of long duration missions. . . . it is imperative that we study more effective and efficient means of rapidly processing and transporting these large volumes of information from their generation point to the ultimate users." [7, p356]

In keeping with this long-term planning approach, the 1984 NASA authorization hearing opened with the following direction given to the NASA officials present: "NASA will continue to grow only if it pays attention not only to the near-term technology requirements but the long-term technology that will be required in the 21st century." [1, p181]

However, an April 1987 GAO report that reviewed NASA's use of information technology concluded with concerns that some areas should be given further review, namely: 1) NASA's space and ground telecommunications systems and their future ability to handle the amounts of scientific data anticipated; 2) NASA's plans to ensure that its ground facilities will be able to communicate, process, distribute, and archive volumes of data in a high quality manner; and, 3) NASA's plans to explore the use of advanced automation in on-board satellite systems. Further, it was not known how much this strategy, with more efficient ground operations, would reduce overall life-cycle costs. [2, p52]

Then, as recently as March 1988, an Information Week article entitled, "NASA's MIS Crashes", leveled the following comments against NASA's data systems (note, MIS stands for Management Information System): "The effects of bad information management permeate and pollute every level of NASA, driving away the best scientists and discouraging new recruits.... And, unlike most corporations, there is no central MIS department to oversee the integration of computer projects.... Researchers say it has often taken years to get data from NASA missions.... NASA's fragmented approach to computers means tapes made on one computer for one project are often incompatible with the computer systems of another project. To share information, NASA scientists may have to wait months for tapes to be reformatted. Even through agency channels, the procedure costs hundreds of thousands of dollars." [3, p8-9]

In a similar vein, the May 1988 issue of Physics Today contained an article which commented: "Failure of the Tracking and Data Relay Satellites or their ground station, for example, could lead to simultaneous loss of all the data from the Hubble Space Telescope, the Gamma Ray Observatory, the Upper Atmospheric Research Satellite and other missions as well.... Current plans for the development of a second TDRS ground station suggest that NASA is, in fact, becoming increasingly sensitive to this situation." [20, p81]

This review is intended to provide information on the flow of space science data from acquisition through NASA's space and ground networks through processing facilities to the researcher or user. The review identifies steps NASA is taking to ensure computing and communications services are carried forward in their long-term plans and that capacity exists for NASA's future science and exploration needs. Additionally, this report discusses cost projections for future space science data handling which NASA may encounter.

Due to the technical nature of the material, notes have been added within this review that include discussions of the various technologies and concepts used in NASA's tracking, communicating, computer processing, and archiving of data. Wherever appropriate, examples have been provided to relate the more abstract concepts to more readily discernible or quantifiable terms. Finally, the Appendix contains a glossary of terms and acronyms that may be useful to the reader.

III. BACKGROUND

To better understand NASA's current communications and data systems environment, it may be helpful to construct a chronology of events leading up to the present. This review may identify constraints that limit strategies that NASA can select, or, on the other hand, it may spur on additional research.

In support of its space program, NASA has a worldwide system of tracking and data acquisition facilities for both Earth orbital and deep space missions. Currently there are three separate tracking systems: the Deep Space Network (DSN), the Space Tracking and Data Network (STDN), and the Tracking and Data Relay Satellite System (TDRSS). Each of these systems will be discussed. Likewise, communications networks and processing capabilities have evolved in an effort to meet data user requirements. These programs are included in this background along with a review of long range studies and plans that were provided over the timeframe of this review.

A. DEEP SPACE NETWORK (DSN)

1. 1958-1978

The DSN's primary role was to provide command, control, tracking, and data acquisition for deep space missions. The network, managed by the Jet Propulsion Laboratory (JPL), consisted of three 64 Meter (210 foot) diameter antennas, five 26 meter (85 foot) antennas, and one 34 meter (modified from a 26 meter) antenna, located at Goldstone, California, Madrid, Spain, and Canberra, Australia, plus a Launch Checkout Station at Cape Canaveral, Florida, and the Space Flight Operations Facility (SFOF) at JPL. The SFOF, which became operational in 1961, is the communication, computation, and control center for the DSN. [4, p117-118]

Concept note: Antenna sizes are dictated by spaceflight mission requirements. Generally, required antenna size is directly proportional to spacecraft distance from earth and data rate. Ground network antennas were built for differing mission objectives. Nine meter antennas were built for low earth orbiters that have short duration passes and required relatively rapid antenna movement.

Twenty-six meter antennas were built for the lunar phase of the Apollo missions. The longer distances associated with planetary and deep space spacecraft necessitate 34 meter and 70 meter antennas to obtain required spacecraft signal levels and data rates.

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2. 1980

At each of the three Deep Space Network locations, NASA converted a 26-meter diameter S-band antenna to a larger more efficient 34-meter diameter S- and X-band antenna. Low-noise X-band maser amplifiers have been installed on the 64-meter diameter antennas. These amplifiers, designed and fabricated at the Jet Propulsion Laboratory, were originally developed under the Advanced Systems program and are among the most sensitive radio receivers ever built. [8, p397]

Concept note: What are the different frequencies used by missions?

NASA conducts most of its work in "space research" allocated spectrum bands at VHF (135-150 MHz), S-Band (2 GHz), X-Band (7/8 GHz), and Ku-Band (13-15 GHz). Planning is underway aimed at utilizing higher frequencies at Ka-Band (20-33 GHz). Eventually, spectrum near W-Band or 60 GHz may be utilized.

The bands used by NASA missions are influenced by a variety of factors, namely, propagation characteristics, bandwidth availability, equipment size and availability, state of technology, ability to share uniquely with other co-allocated activities, and the regulatory availability (frequency allocation) for space type activities.

Deep space missions usually operate within specific parts of S-Band, X-Band, with future wideband systems being targeted for Ka-Band. Low earth orbiting missions, on the other hand, operate at VHF, S-Band, and Ku-Band. NASA's space network, the Tracking and Data Relay Satellite System (TDRSS), operates at both S-Band and Ku-Band in supporting "client" spacecraft.

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3. 1985

By 1985 the DSN evolved into a highly capable network that proved sensitive to the requirements of deep space missions and has been used in related scientific research. According to the 1985 hearings on NASA's long range plans, the next major changes to the DSN may occur around the year 2000 when NASA may pursue development of a deep space relay system with possible operation to commence around 2008. [10, p175]

4. 1986

NASA officials assessed the value of the DSN not only for deep space missions but also for those Earth orbiting spacecraft that cannot be supported by the TDRSS. (For example, highly elliptical Earth orbiters cannot be well served by the TDRSS.) The network can also provide limited support of TDRS spacecraft in cases of emergencies. Additionally, DSN facilities are used in related scientific research, such as the use of radar techniques to measure objects in the solar system, the search for the existence of gravity waves, as well as the mapping of locations of extragalactic radio sources. [11, p345]

5. 1987

During the 1988 Authorization hearings, NASA officials disclosed that 64 meter antennas were to be enlarged to 70 meters to provide better reception.

B. SPACEFLIGHT TRACKING AND DATA NETWORK (STDN)

1. 1958-1978

The STDN is used for tracking Earth-orbital missions, manned and unmanned, and is managed by Goddard Space Flight Center. STDN resulted from the 1972 consolidation of the formerly separate Space Tracking and Data Acquisition Network (STADAN) for unmanned missions and the Manned Space Flight Network (MSFN) for manned missions. The combination was made to bring the budget structure into alignment with NASA's longer-range plan to merge the capabilities of the two networks into a single integrated network of fewer stations to support all Earth-orbital missions. [4, p126]

In the 1977 NASA budget authorization hearings, NASA officials pointed out that inflation in the area of wages and salaries had an annual cost escalation effect of 6-7% on network operations. Therefore, savings that were associated with station closings and other reductions were offset by inflationary salary costs. [6, p793]

2. 1980

NASA documents that were provided for a September 1980 program review hearing indicated that the STDN was currently supporting about 50 active spacecraft. Included were the Landsat 2 and 3, Solar Maximum Mission, High Energy Astronomy Observatories, and the International Ultraviolet Explorer Satellite. [8, p394]

However, in those same documents, NASA officials pointed out that most of the equipment in the STDN network had been installed in the mid 1960's to support the Apollo spacecraft program. Thus, delays in launch dates for TDRSS would require NASA to maintain and operate ground stations with obsolete systems they had planned to close based on an earlier TDRSS deployment. [8, p395]

3. 1983

In hearings on the 1984 budget, NASA provided, for the record, information on manpower savings that would result from the streamlining of DSN and STDN sites whenever the TDRSS is fully implemented: "The area being addressed here is related to the manning level of the NASA ground network which includes the Deep Space Network (DSN) and the Spaceflight Tracking and Data Network (STDN). The manning level at the ground network in FY

1983 is approximately 1,530. After the network consolidation program is complete, the level at the ground network will decline to approximately 875, when only the following stations will be open: Bermuda, Greenbelt, Merritt Island, Goldstone, Madrid, and Australia." [1, p208]

4. 1986

NASA reaffirmed that further closings of ground stations would be dependent upon having two fully operational TDRS in orbit. [11, p323]

5. 1988

Memoranda of Agreement (MOA's) are in place for the eventual transfer of the Guam and Hawaii STDN sites to the DoD (Department of Defense). An MOA is being worked for Ascension. The Santiago facility will be turned over to the University of Chile when NASA is completed with its use (upon placing two more TDRS craft into position) which is currently estimated for September 30, 1989.

C. TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS)

1. 1958-1978

The TDRSS was originally planned to consist of an operational constellation of four spacecraft in geosynchronous orbit, a ground terminal at White Sands, NM (White Sands Ground Terminal or WSGT), and scheduling and communications facilities at the Goddard Space Flight Center (GSFC) in Greenbelt, MD. Two of the spacecraft were to service NASA: one over the mid-Atlantic at 41 degrees west longitude, the "east satellite"; another over the mid-Pacific at 171 degrees west longitude, the "west satellite". Positioned between these two was to be an Advanced Westar satellite which would provide commercial service as a domestic communications satellite and serve as a spare (at 79 degrees west longitude) for the maintenance of both services. [5, p368] (See Figure 1)

The TDRSS was designed to handle NASA's Earth orbital tracking and as it became operational, to permit NASA to close 9 of its 13 ground stations and to consolidate the remaining stations with the DSN. The remaining STDN stations would be required for spacecraft in highly elliptical Earth orbits and launch support. [5, p367] The DSN would still be required when TDRSS was fully implemented.

One objective of deploying the TDRSS was to reduce the operations budget of the Office of Space Tracking and Data Systems (OSTDS) by closing earth stations which were labor intensive. For example, in fiscal year 1979, 60 percent of the increase for the OSTDS operations budget, $17 million, was related to increases in salaries and fringe benefits for tracking station employees. [4, p140]

The TDRSS reception facility at White Sands was constructed with three 18 meter (60 foot) antennas for the east, west, and central TDRSS spacecraft, and associated telemetry and simulation antennas.

Tracking and Data Relay Satellite System.

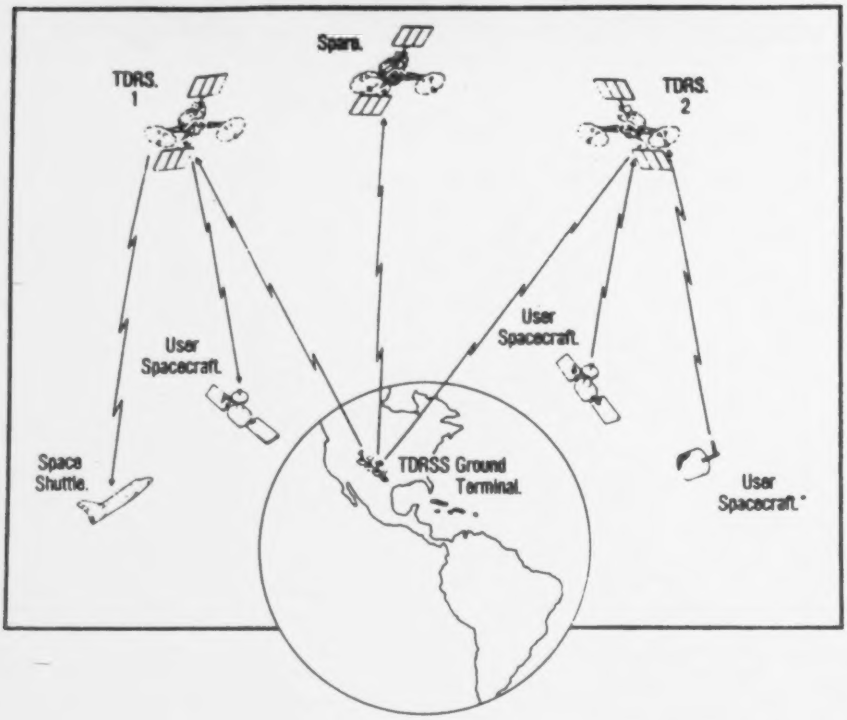

Spare.
TDRS.
1
TDRS.
2
User
Spacecraft.
User
Spacecraft.
Space
Shuttle.
TDRSS Ground
Terminal.
User
Spacecraft.*

FIGURE 1 [5, p369]

The east and west satellites, to be used by NASA only, were intended to provide full coverage for satellites in orbits higher than 1,200 kilometers and at least 85 percent coverage for satellites in lower orbits. The location of the two NASA TDRSS craft gives each one a wide coverage area unblocked by the Earth's horizons. The two-satellite system has the capability to serve 24 spacecraft simultaneously.

The TDRSS (including the spare) was intended to provide data relay service for up to 26 users at the same time with data rates that range from 100 bits per second (bps) to 300 mega (million) bits per second (Mbps) plus accurate tracking data for user orbit determination. Communications between a TDRS and users will be at frequencies in the S- or K-band depending on specific data rates and requirements.

Concept note: Bit is a contraction of "binary digit", the smallest unit of information in a binary system. A bit represents the choice between a mark or space (one or zero) condition. A byte (pronounced bite) is a small group of bits of data that is handled as a unit. In most cases it is an 8-bit byte.

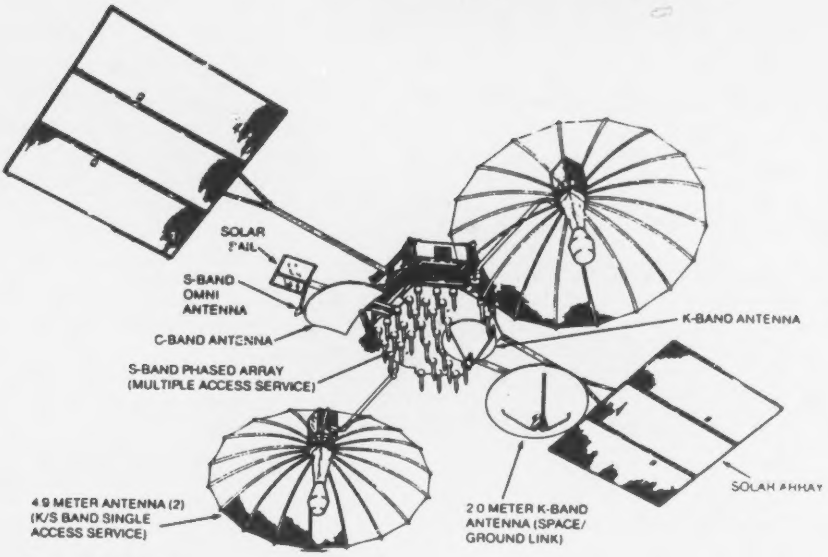
K-band antennas at WSGT allow command, telemetry and tracking for each satellite along with the total uplink and downlink activity with user spacecraft. Launch and emergency control of all TDRS is provided by S-band tracking, telemetry and command (TT&C) antenna placed in such a position that it possesses the greatest unblocked field in the group of antennas.

Each TDRS is solar-powered and has two high gain 4.9 meter parabolic antennas, each with potential S-band or K-band service to a spacecraft. There is also an electronically steerable phased array antenna, known as the multiple access system, which can communicate with as many as 20 low data rate users simultaneously. Operating at S-band, the multiple access limits each user to a data rate of 50 kilobits per second (Kbs). The single access antenna can go as high as 300 Mbs at K-band. [5, p370] (See Figure 2)

Concept note: Capacity of a communications line or link

Generally, communications capacity is cited in Megabits (millions of bits) per second. In order to place these numbers in perspective, consider the phonebook of a large city. The Washington, D.C. phonebook has about 850 pages of telephone listings. Each page has about 400 telephone numbers. Thus there are about 340,000 entries. Each entry has about 40 characters and each character equals 8 bits. By multiplication, we find this phonebook has about 109 megabits of information. Thus a communications circuit designed for 300 Megabits (Mbs) per second, nearly has capacity to transmit three entire phonebook's worth of information every second. As another example, a fast typist types one word per second. The word, on the average, contains five characters and a space or 48 bits. Thus, 300 Megabits per second is the amount of data generated by 6,247,500 very fast typists, working in unison.

TRACKING & DATA RELAY SATELLITE (TDRS)


SOLAR SAIL
S-BAND OMNI ANTENNA
C-BAND ANTENNA
S-BAND PHASED ARRAY (MULTIPLE ACCESS SERVICE)
K-BAND ANTENNA
SOLAR ARRAY
4.9 METER ANTENNA (2) (K/S BAND SINGLE ACCESS SERVICE)
2.0 METER K-BAND ANTENNA (SPACE/GROUND LINK)

Source: Spacecom.

FIGURE 2 [5, p371]

In October 1973, Congress was approached by NASA with an outline for a TDRSS. At that time, the possibility for a leased system was one of several alternatives being considered by NASA for financing the project. [5, p372]

In January 1974, a full analysis of TDRSS was presented to congressional committees by NASA's Office of Tracking and Data Acquisition (OTDA) (later renamed the Office of Space Tracking and Data Systems). OTDA recommended that TDRSS be procured on a leased system basis whereby a contractor could either provide service dedicated to NASA or incorporate such capabilities in a spacecraft system shared with other services, but TDRSS design would reflect NASA studies. NASA planned a 10-year leasing period in which the contractor would operate both the space and ground segments. [5, p373]

Section 6 of the 1978 NASA Authorization Act (Public Law 95-76a) gave NASA the necessary authority to enter into the TDRSS lease arrangement. [5, p374]

In December 1976, NASA awarded the TDRSS contract. Terms of the original TDRSS contract provided for 10 years of TDRSS service to begin when the system was accepted as operational by NASA, at that time scheduled for December 31, 1979. The contract had a fixed price of $786 million, with an additional maximum award fee of $10 million, for a total of $796 million or approximately $80 million annually, subject to adjustment for changes to planned labor rates, material costs and interest rates as a result of economic fluctuations. [5, p375]

The Federal Financing Bank (FFB) made loans guaranteed by NASA, to the contractor, to finance the TDRSS. When lease payments began, NASA would have to make principal and interest payments on the loan. The contract was adjusted for variations in interest fluctuations from the 7.5 percent contract baseline rate. Adjustment for variations in actual launch vehicle costs, actual costs of State and local taxes, and for inflation above 5.5 percent or below 4.5 percent for part of the labor and material, were also included in the contract. [5, p376]

In 1977, Operations Research, Inc. (ORI) prepared a study for NASA which attempted to appraise the value of TDRSS against continuation of the STDN. Their findings focused on three factors: 1) reduced costs of operating and equipping the STDN; 2) decreasing the deficit in the U.S. balance of payments; and, 3) improved flexibility and efficiency of NASA spacecraft and space shuttle operations. [26, pii]

The ORI study estimated the first factor, cost of modifying and operating STDN without the TDRSS over the period of 1977 to 1990 would be $467 million greater than maintaining STDN with TDRSS (in 1977 dollars). [26,piii] On the next factor, the balance of payments, ORI estimated the TDRSS would decrease payments associated with foreign-based ground stations by $362 million between 1980 and 1990 (in 1977 dollars). [26, piii]

On the third factor, although the ORI study recognized in its review that the TDRSS could monitor earth orbit spacecraft 85-100% of each orbit, instead of STDN's 15%, they did not price this value. Yet, the study did point out benefits provided by the TDRSS: practical real time control;

nearly continuous voice communications with Shuttle operations; and, avoidance of extensive wide-band circuits that future workloads would have required. [26, piii]

2. 1979 (Contract Modifications)

The TDRSS program encountered a series of problems between 1976 and 1979. The most significant of these was a potential radio frequency interference (RFI) problem that arose after the satellites had been designed and partially built, making the correction a costly one. Negotiations between NASA and Western Union on these and other disputes proceeded during most of 1978. A settlement was reached and the TDRSS contract was amended in February 1979. [5, p376] By the time modifications required to correct the RFI problem were implemented and cost settlement reached for other adjustments, the NASA cost increase was $75 million. The total TDRSS cost had risen to $876 million for the 10-year lease period. [5, p378]

3. 1980

During hearings on its fiscal 1981 budget request, NASA announced that TDRSS program cost would exceed $1.4 billion, $619 million more than the original contract price and $539 million higher than the settlement made a year earlier between NASA and Western Union. NASA attributed more than one-third of the cost escalation, $225 million, to a delay in the shuttle schedule. The first TDRSS launch, scheduled for the first operational mission, had to be moved from December 1980 to March 1982.

The loan from the FFB, on which NASA had agreed to pay interest in the original contract, had to be revised each time the TDRSS program was delayed. The principal on the loan remained the same, but with every delay, the term of the loan was extended, since the borrowing period is dependent on the launch date. NASA officials estimated TDRSS costs were increasing $13 million per month of slippage at that time. [5, p378]

NASA reported in the September 1980 budget hearings that the TDRSS ground station at White Sands was making very good progress toward completion, but they had already determined that more capable computers were needed in the terminal and long term services would depend upon replacing the current computer configuration. [8, p399]

4. 1981

In 1981, NASA budget estimates reflected an even higher total cost for TDRSS, $1.8 billion for the 10-year service. This estimate was based on a September 1982 launch date for TDRSS/A. Most of the cost increase was attributed to interest build-up as a result of launch delays. Under the legislation that allowed NASA to enter into the TDRSS contracts, payments on the FFB loan (including interest costs) cannot begin until the service had started. [5, p379]

In March 1981, NASA released an audit report by the agency's Office of the Inspector General (IG) on the Tracking and Data Relay Satellite System. According to the report, NASA's share of the TDRSS program cost was estimated to be $2.156 billion. The biggest contributor to increased TDRSS costs was interest on the 10-year loan from the FFB. Total interest cost escalated to $689 million, an increase of $469 million since the contract was signed in 1976. [5, p380]

5. 1983

In hearings for NASA's 1984 authorization, NASA officials testified that OSTDS's 1984 budget increase was due primarily to three elements. First, an increase was required to provide a full year's funding for TDRSS service which included loan payments to the Federal Financing Bank. Second, there was a modest inflation provision for operating and equipping various ground support facilities. And, third was the consolidation of budget responsibility to the Office of Space Tracking and Data Systems for the program support communications network which handles data, facsimile, and teleconference circuits among headquarters, NASA centers, and contractors. [1, p184]

The annual payments to the FFB for TDRSS were projected at $30.1 million for FY 1983, $196.7 million for FY 1984, and $210.8 million for FY 1985 and subsequent years. [1, p204]

In the same hearings, NASA related that, although TDRSS had been conceived as a shared system to provide both commercial and government mission support capabilities, the contract had been modified in December of 1982. This modification gave NASA dedicated use of all six spacecraft. The operational constellation of satellites would consist of three, rather than four spacecraft. This change would potentially extend system life since there will be three replacement spacecraft on the ground to restore full NASA service in the event of spacecraft failure or degradation. Before the modification, there were two replacement spacecraft to back up NASA and commercial flight interests. [1, p185]

6. 1985

In hearings on NASA's Long Range Plans, NASA witnesses first notified Congress that plans were underway for a second site in the White Sands ground station area to support TDRS and any follow-on spacecraft and to reduce the vulnerability that a single site places on the system if it should fail. The second site would also allow NASA to have a configuration where more than two satellites are operating. [10, p149]

In response to questions regarding a 10 degree gap in coverage over the Indian Ocean and whether the second facility at White Sands would provide that coverage, NASA disclosed plans to locate two operating satellites in the east and two operating in the west to meet future mission data requirements. A four satellite configuration with all operating would provide eight antennas for missions but does not close the low Earth orbit gap over the Indian Ocean. Although not specific on the timing for a four satellite TDRSS, the mid-1990's were framed as a point in the space station era where the data rate might warrant it. [10, p150] (See Figure 3, the shaded area is the zone of exclusion.)

Concept note: TDRSS coverage limitations

The TDRSS has coverage limitations due both to earth shadow (the Zone of Exclusion (ZOE)) and to antenna field of view (FOV). The ZOE (the area in which communications coverage cannot be provided) is centered over 74 degrees E.; it starts as a point at an altitude of 1200 km (kilometers) and expands as altitude decreases.

The amount of coverage is a function of the user's spacecraft altitude and inclination. Users above 1200 km are not affected by the ZOE. Users at low altitudes and inclinations may pass through the ZOE once per day or less, although the duration of the passage will be greater than for a low-inclination mission. For a 200-km orbit, the minimum coverage is 85 percent. While TDRSS low altitude coverage is limited by earth shadow, high altitude coverage is limited by the fields of view of the TDRS antennas. Coverage for the MA (multiple access) users begins to decrease as orbits exceed 2000 km, due to the MA antenna's +/-13-degree conical field of view. For SA (single access) users, the high-altitude coverage constraint is the SA antenna gimbal mechanical limits. The pointing range is specified as +/-22.5 degrees (east-west) and +/-31.0 degrees (north-south), resulting in coverage limitations for users above 11,000 km. (See Figure 3A for a visual of this concept.)

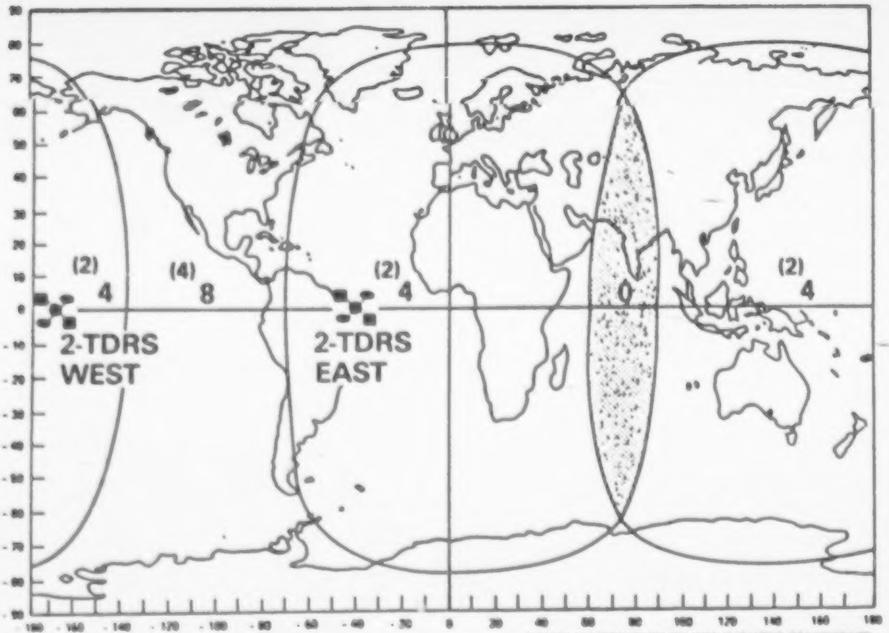
---

7. 1986

For FY 1987, NASA estimated the cost of the second ground terminal for TDRSS to be $22 million. [11, p280] The site selected is approximately 3 miles from the existing ground terminal and construction would begin in FY 1987 and then be available in 1991 to 1992, if funding was approved. [11, p328]

NASA reconfirmed that the second TDRS when launched would be placed at 171 degrees W Longitude, the third at 41 degrees W, and then the TDRS-1, which was not performing properly, would be moved to a central position and used as the spare. [11, p334]

SPACE SEGMENT CONTINUATION (4 SATELLITE SA COVERAGE CONCEPT)


(2)
4
(4)
8
(2)
4
0
(2)
4
2-TDRS
WEST
2-TDRS
EAST
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
180

( ) PRESENT SYSTEM

TDRSS COVERAGE OF 200 NMI ALT USER SPACECRAFT
TDRS LOCATIONS 41W, 41W, 171W, 171W

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REV. 6 10 86

FIGURE 3 [10, 167]

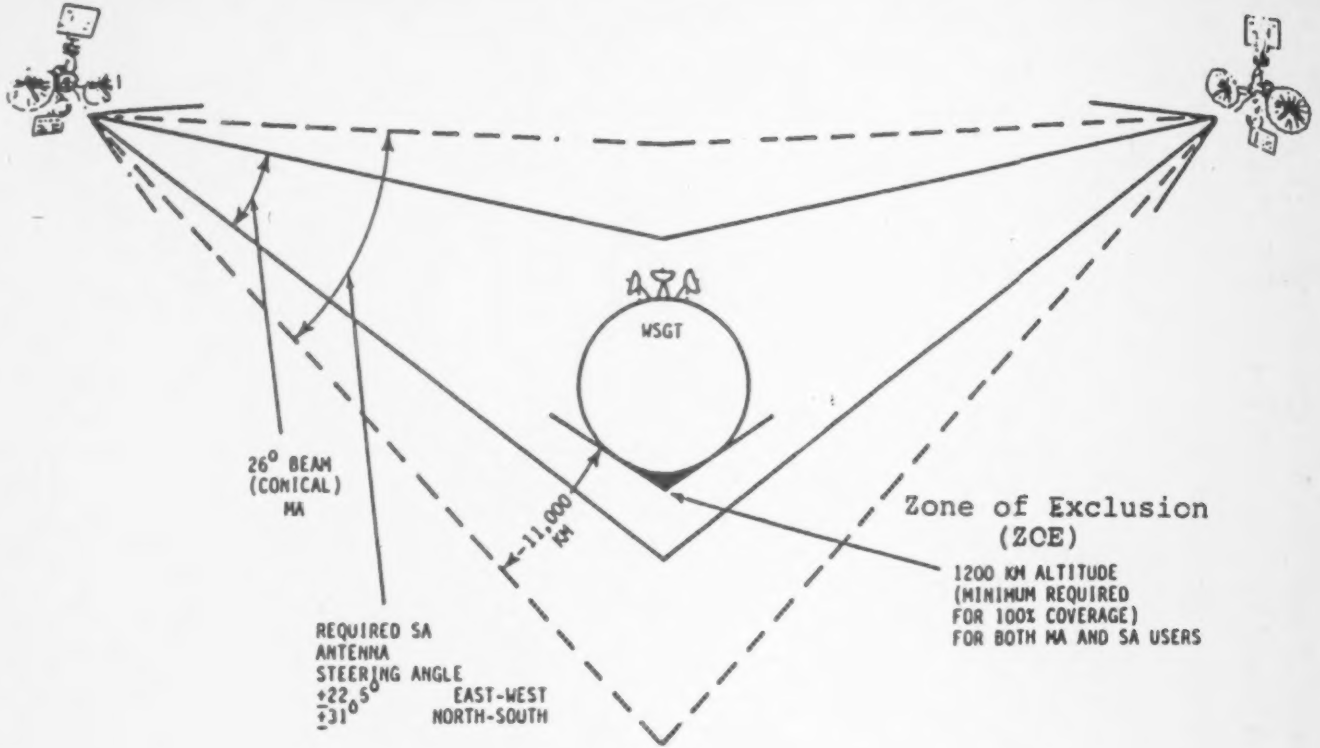

WSGT
26° BEAM
(CONICAL)
MA
REQUIRED SA
ANTENNA
STEERING ANGLE
±22.5° EAST-WEST
±31° NORTH-SOUTH
~11,000 KM
Zone of Exclusion
(ZOE)
1200 KM ALTITUDE
(MINIMUM REQUIRED
FOR 100% COVERAGE)
FOR BOTH MA AND SA USERS

FIGURE 3A [19, p1-11]

Discussions of the FY 1987 budget also focused on the effects of the Challenger accident which resulted in the loss of its TDRS payload. NASA requested a $50 million increase to accelerate the ongoing program for the next several spacecraft. Since TDRS-2 was lost in the Challenger accident, a separate procurement for an advanced TDRS spacecraft was undertaken. [11, p328]

8. 1987

During hearings on the FY 1988 request for NASA, the Committee addressed the data rates for the space station and TDRSS's capability to meet those rates. NASA reiterated that the capability of TDRS is 300 megabits per second, and that, two TDRS's with one back-up in space will meet service data requirements until the space station is operational. At that point, the constraining factor for tracking will be the number of TDRS antennas which are in orbit; therefore, NASA will put the four TDRS satellites into space. Officials further outlined that plans were to have the replacement spacecraft (1, or possibly 2) in the 1991-1992 timeframe. Then, advanced technology satellites to replace the current TDRS would become available in the late 1996 timeframe. [12, p167-168]

NASA also presented a TDRSS launch schedule: TDRS-3 for February 1988; TDRS-4 for September 1988; TDRS-5 as soon as possible, hopefully by Fall 1989, to replace TDRS-1; and TDRS-6 will be stored. [12, p194]

9. 1988 (NASA Briefing)

On May 19, 1988, NASA officials held a press conference to detail plans for launching the TDRS. The briefing indicated the following schedule information:

Date:	Activity:
Aug 88	Launch TDRS-3
Jan 89	Launch TDRS-4
Jul 90	Launch TDRS-5
1992	Complete 2nd Ground Terminal at White Sands
May 92	Launch TDRS-6

D. NASCOM (NASA COMMUNICATIONS SYSTEM)

1. 1965-1982

NASA's satellite control centers, antenna stations and data processing facilities are linked together via a global communications system called NASCOM (NASA Communications System) utilizing telephone, microwave, undersea cable and satellite links, leased from domestic and foreign common carriers. Before the 1965 formation of NASCOM, each of NASA's three tracking networks had a separate communications system. [4, p121]

2. 1983

In NASA's Five Year Plan, the Office of Space Tracking and Data Systems' portion discussed NASCOM at length. First, as it existed: NASCOM had over 2.5 million circuit miles - domestic and foreign, both satellite and terrestrial and nearly all leased. There were 630 circuits to 139 stations providing voice, data, video, analog, digital, narrow-, and wide-band service. NASCOM also had a broadcast mode video system to all NASA centers. There were 21 collocated domestic satellite (DOMSAT) stations at 11 NASA sites. Major switches were at Canberra, Madrid, and JPL, and the control center was at the Goddard Space Flight Center. [9, p125]

Additionally, NASA provided insight into future plans for NASCOM. It would evolve into a complex common user network made up of wideband digital links. Using fiber optics for wideband interfaces and for local distribution, NASCOM would use TDMA (Time Division/Multiple Access) techniques for demand assigned voice, and high speed data and video. NASA anticipated this plan would help stabilize operations costs through both improved technology and a competitive marketplace. [9, p126]

3. 1986

NASA reported that the TDMA system, which will provide operational circuits via satellite which can be readily configured among NASA facilities to dynamically service workload requirements, will be completed in FY 1986. [11, p341] The existing 15 Mbs communications network that is being used by NASCOM will provide operational support to NASA missions and will be augmented by a 60 Mbs capability at major operational sites in FY 1987. This capability will provide more effective use of communications satellite transponders, and will improve services throughout the Agency. [11, p347]

E. CONTROL CENTERS

1. 1980

NASA reported that the Office of Space Tracking and Data Systems (OSTDS) was operating six control centers to meet operational support requirements for some 20 to 25 spacecraft. Furthermore, they had recently contracted for the design, development, and implementation of a new and dedicated control center to support the Space Telescope mission. [8, p395]

F. SUPPORT COMPUTING ACTIVITIES

1. 1980

The major functions conducted in this category involve providing near real time support to spacecraft operations like orbit determination, attitude determination, and command memory management. The large computer complex providing this support was some 15 years old. Thus, with Congressional agreement, OSTDS undertook a sequential replacement of these several computer systems. [8, p395]

NASA reported that as they moved into the TDRSS era, data volume would increase by approximately a factor of four; moreover, there must be work on ways to deliver mission data primarily in a real-time mode to its many dispersed users. Work continues on testing fiber optics as a mean of distributing high data rates (up to 50 Mbs) between computers and payload processing centers. NASA planned to begin a Phase II testing during FY 1981 on data speeds up to 100 Mbs. [8, p404]

2. 1983

NASA noted that bulk science data processing from various spacecraft is a significant support function. In fiscal 1984, they will continue to process both digital and image data from scientific and applications space programs. A major addition was a facility to process data from Spacelab and other missions. Also, NASA requested $14.2 million for advanced system program studies to aid in planning and to assure more efficient and cost-effective mission support in the future. [1, p187]

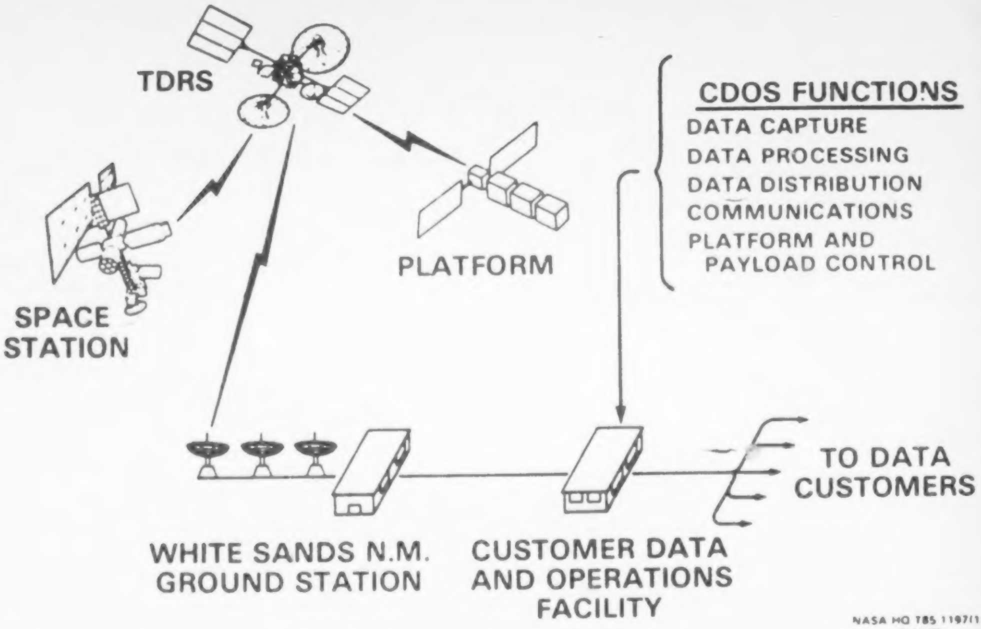
In the same year, NASA officials reviewed the Five Year Plan and added to the hardware replacement program and noted that efforts were underway to incorporate new and more efficient software to perform computations needed to support mission operations and control of spacecraft.

During hearings on the Five Year Plan, a question was posed whether a major part of the computer processing problem was created by the amount of data flowing through the system and the volume of data waiting to be processed and analyzed. The response was that probably there is always more data collected than one can fully analyze, although many researchers and graduate students go back and look at data years later and extract new scientific information from it. NASA further elaborated that its role is to capture the data, organize it in a fashion that can be delivered to the researcher for his use and that's where NASA's task stops. Once data is transferred to another institution, NASA does not control it. [9, p139]

3. 1985

NASA officials detailed improvements they foresaw for processing in the future. The customer data and operations system would bring data through a TDRSS satellite to White Sands and then be transmitted to the facility. At this location, processing would order the data, and then communicate it out to the users. [10, p152] (See Figure 4)

CUSTOMER DATA AND OPERATIONS SYSTEM (CDOS) PLANNING FOR THE SPACE STATION ERA


TDRS
SPACE STATION
PLATFORM
WHITE SANDS N.M. GROUND STATION
CUSTOMER DATA AND OPERATIONS FACILITY
TO DATA CUSTOMERS

CDOS FUNCTIONS
- DATA CAPTURE
- DATA PROCESSING
- DATA DISTRIBUTION
- COMMUNICATIONS
- PLATFORM AND PAYLOAD CONTROL

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9 11 85

FIGURE 16

FIGURE 4 [10, p170]

G. PSC (PROGRAM SUPPORT COMMUNICATIONS)

1. 1983

In NASA's Five Year Plan, the section on the Office of Space Tracking and Data Systems included insights into PSC, the non-operational communications activities. The PSC as detailed was comprised of 345,000 circuit miles, both satellite and terrestrial, with network control at Marshall Space Flight Center. PSC could support data rates of 110 bps to 56 Kbs and had packet switched networks at 11 locations. NASA projected 4,600 voice teleconferences over PSC from its 75 voice teleconference rooms in FY 1983 as well as supporting 134 high speed fax and 149 low speed fax stations, and the users of 510 electronic mail mailboxes. [9 p128]

In terms of future growth, NASA saw PSC growing into a network, the PSCN (the Program Support Communications Network). It would build on a common user integrated network consisting of gateways at 14 locations, transmission speeds into the range of 1.5 Mbs with a network control center at Marshall Space Flight Center. The PSCN would provide all of the services of PSC plus super computer data links, video teleconferencing, FTS service between NASA facilities, and FTS support to GSA. [9, p129]

2. 1986

During 1987 authorization hearings, NASA reported that the PSCN would be completed in 1986. [11, p341] Consolidation of the many requirements levied on the Marshall Space Flight Center into a single network allows rapidly increasing communications needs to be met more effectively and economically. [11, p348]

H. LONG RANGE STUDIES/PLANS

1. 1978

The Space Science Board of the National Research Council formed the Committee on Data Management and Computation, CODMAC. The scope of CODMAC considerations encompassed all space acquired data, whether derived from scientific or applications missions. The Committee's charge was specifically to examine: 1) Data System Planning; 2) Preprocessing; 3) Distribution of Data; 4) Data Standardization and Fidelity; 5) Software Development; 6) Distribution of Computational Capabilities; 7) Mass Data Storage and Retrieval; and 8) Interactive Processing. [16, p xi]

2. 1980

In September 1980, the Office of Space Tracking and Data Systems reported that as the space program matures and expectations on data products grow, demands on the data system may increase almost exponentially. Therefore, NASA undertook a study of the overall system performance and various techniques and technologies to better meet the requirements levied on their data systems. This work would be coordinated with the NASA End to End Data Systems (NEEDS) study activities which had been underway for several years. [8, p396]

Included in the Office of Space Tracking and Data Systems portion of the NASA Five-Year Plan presented in 1980 were the following objectives: 1) Continue working toward successful launch and operation of the TDRSS; 2) Ground tracking stations redundant to services of TDRSS will be closed as support needs decline; 3) STDN and DSN will be reconfigured into one general purpose network under management of JPL; 4) Reception capability and sensitivity of the ground stations will be extended; 5) New concepts and techniques will be explored for acquiring, processing, transferring, and managing data, improving data handling efficiency, and reducing costs; and 6) Study will continue on second generation communications-relay satellites in geosynchronous orbit to support Earth-orbital missions and possibly even deep space activities in the 1990's. [8, p405]

3. 1982

In 1982, CODMAC released its report which was primarily directed to NASA and the problems of data flow in the future. The study concluded with a list of 21 recommendations presented under three categories of policy, technology, and general. Among these recommendations were:

- Policy: 1) Active involvement for scientists in planning and implementing acquisition, processing, archiving, and distribution of data should be strongly encouraged and supported; and 2) Data-analysis funds should be adequate and protected against reprogramming as the result of such occurrences as hardware overruns and mission time delays.

- Technology: 1) NASA should have an ongoing technology management activity encompassing all areas of data systems; 2) NASA's approach to technology development from the component level to systems level should emphasize the capability to implement new technologies rapidly as they evolve; 3) NASA should become more active in the area of satellite communications technology and should set a goal of increasing uplink capabilities to satellites by an order of magnitude in the 1980's; 4) Electronic transfer of data to investigators should be implemented where economically feasible; and 5) NASA should examine its current technology development efforts to determine whether they are duplicating developments now underway in industry, DOD, or other government agencies.

- General: 1) Greater emphasis should be given to documentation of space-science and application data to make them interpretable and useful to scientists not directly associated with initial acquisition of data; 2) Under scientific overseers, NASA should vigorously pursue the archiving and preservation of such space-science data that should be permanently stored, and data no longer required for future scientific uses should be purged; 3) More emphasis should be given to the production of user-oriented catalogs and browse files for space-science data; 4) NASA should work closely with the scientific community to adequate computational capabilities, communications facilities, etc.; 5) Computational hardware, software, and interactive terminals should be updated more frequently to keep up with the space science data loads and developments in computer technology; and 6) Greater consideration should be given to preprocessing and data compaction schemes and to artificial intelligence and robotics. [16, p6-11]

4. 1983

NASA's discussions of the Five Year Plan touched on some continuing activities toward overall data systems planning. In preparation for the Space Station, JPL was conducting an end to end information systems study. Preliminary user needs were identified and a system architecture was conceptualized. Future work would include ground/space trade-off studies, and NASA was projecting increased center participation in follow-on studies. [9, p133]

5. 1983 (TDAS, THE TDRSS FOLLOW-ON)

NASA's presentation of the Five Year Plan included a look into the future at a satellite for the post-TDRSS era, the Tracking and Data Acquisition System (TDAS). A two-year study was nearing completion which included looking at the type of missions that were due in the future (300-600 Mb ranges). Some of the technologies needed that were identified in systems definition were: W-band (60 GHz) systems, multi-beam antenna switching, and laser satellite-to-satellite linking. The technology studies were scheduled to start in FY 1984. NASA officials noted that, given the 10 to 15 years it takes to bring a new system to fruition, they needed to look at the mid-1990's when missions would need the next generation spacecraft. [9, p136] (See Figure 5)

6. 1985 (TDAS)

In hearings on NASA's Long Range Plans, officials provided a concept outline of how the TDAS would be configured when it was deployed. [10, p173] (See Figure 6) Also, a planning schedule was included which contained time lines for TDRS, the TDRS follow-on (TDAS), and deployment of a deep space relay system. [10, p175] (See Figure 7)

In response to questions about the use of laser technology and how it would permit the TDAS to utilize megabit-per-second transmission capability, NASA provided the following for the record: "The Space Tracking and Data Systems Program has a laser communications study with the Goddard Space Flight Center which is under way for the Tracking and Data Acquisition System (TDAS)-- planned as the 2nd generation TDRSS. This effort is expected to provide conceptual designs of three types of laser terminals. . . This study will aid in the determination of whether these links will use microwaves or optics. . . . With the successful completion of these

TDAS TECHNOLOGY

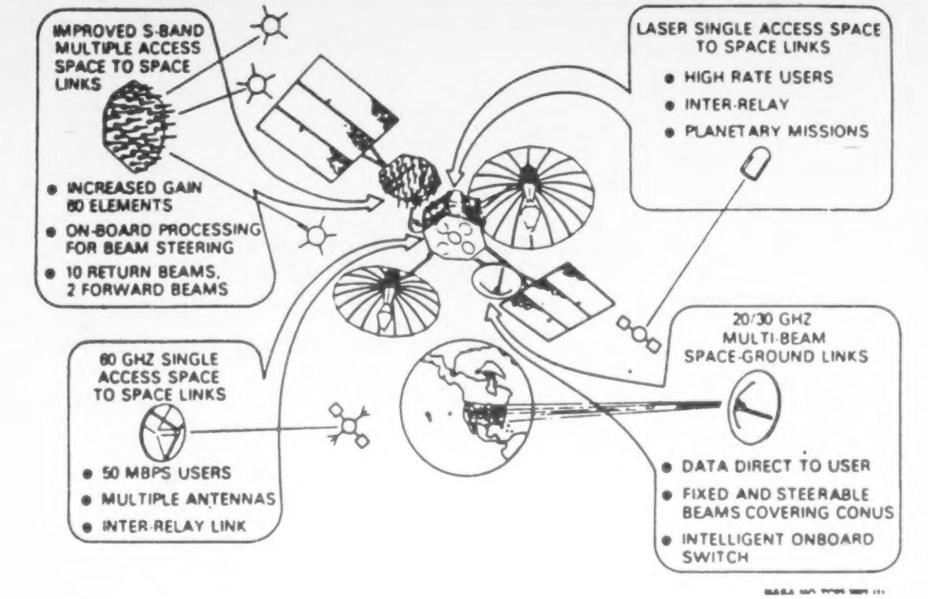
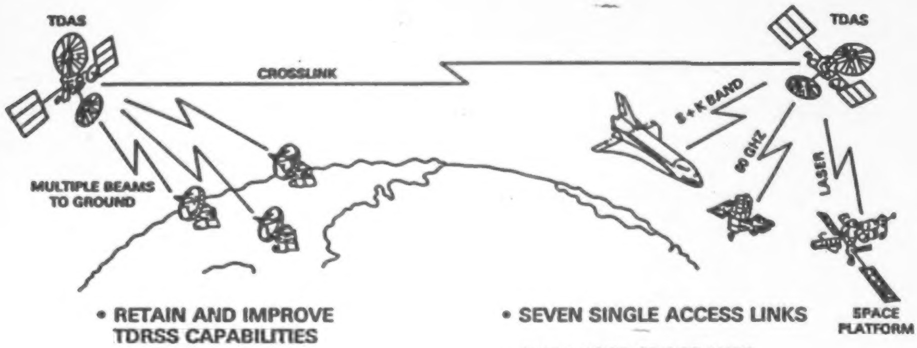

IMPROVED S-BAND MULTIPLE ACCESS SPACE TO SPACE LINKS
• INCREASED GAIN 60 ELEMENTS
• ON-BOARD PROCESSING FOR BEAM STEERING
• 10 RETURN BEAMS, 2 FORWARD BEAMS
LASER SINGLE ACCESS SPACE TO SPACE LINKS
• HIGH RATE USERS
• INTER-RELAY
• PLANETARY MISSIONS
60 GHZ SINGLE ACCESS SPACE TO SPACE LINKS
• 50 MBPS USERS
• MULTIPLE ANTENNAS
• INTER-RELAY LINK
20/30 GHZ MULTI-BEAM SPACE-GROUND LINKS
• DATA DIRECT TO USER
• FIXED AND STEERABLE BEAMS COVERING CONUS
• INTELLIGENT ONBOARD SWITCH

FIGURE 5 [9, p136]

TRACKING AND DATA ACQUISITION SYSTEM (TDAS) FOR THE YEARS 2000^+


TDAS
CROSSLINK
TDAS
S+K BAND
60 GHZ
LASER
MULTIPLE BEAMS TO GROUND
SPACE PLATFORM

- RETAIN AND IMPROVE TDRSS CAPABILITIES
- NO BLIND SPOTS
- UP TO NINE DIRECT LINKS TO GROUND
- SEVEN SINGLE ACCESS LINKS
- ONE LASER CROSS LINK, ONE Gb/s DATA RATE
- ONE LASER SPACE-TO-SPACE LINK, ONE Gb/s DATA RATE

FIGURE 6 [10, p173]

PLANNING SCHEDULE
MAJOR FUTURE CAPABILITIES

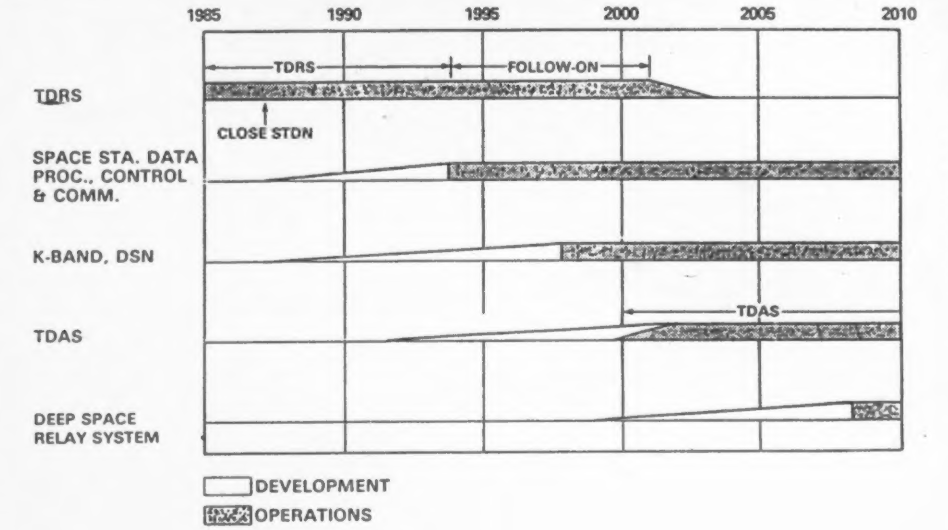


FIGURE 7 [10, p175]

activities, substantial system level benefits result which can be used to increase data rate, reduce size and weight, and increase performance margins." [10, p177]

7. 1986 (TDAS)

FY 1987 authorization hearings helped to clarify NASA's plans for the TDRS follow-on spacecraft and for TDAS. A request for $39 million for FY 1987 was to purchase the additional spacecraft to carry the TDRSS program through the mid-1990's. At that point, NASA would use spacecraft using newer technologies. [11, p351]

8. 1986 (CODMAC follow-on to study released in 1982)

The 1986 release of "Issues and Recommendations Associated with Distributed Computation and Data Management Systems for the Space Sciences", by the National Research Council, provided a follow-on to the study of 1982. The new study indicated that since the release of the earlier report, dialogues among members of CODMAC, NASA, and the space science community had been fruitful and steps taken to meet some of the issues and to correct some of the problems. These steps included: "(1) consolidation of a number of management activities under the Information Systems Office of the Office of Space Sciences and Applications of NASA; (2) initiation of pilot data systems by that office to improve computation and management of data in various space science disciplines; (3) consideration of data problems and solutions by the solar and space physics community. . . .; (4) initiation of a Computer Sciences Program in the Office of Applications and Space Technology, NASA; and (5) an evaluation and restructuring of the role of the National Space Science and Data Center."

On the other hand, the study noted that although progress had been made, overall vision was still lacking within NASA as to what requirements scientists will have for systems to handle, process, and store given the significant quantities of data expected from future missions. "The importance of computation and data management associated with extraction of scientific information cannot be understated. In fact, the information and knowledge extracted from space science data should be the ultimate measure of mission success." [17, pviii]

The study further noted that projected rates of growth of spaceborne data over the next decade for the planetary sciences, astronomy, solar and space physics, and the earth sciences can be modeled with exponential growth functions, with doubling periods averaging only a few years. Accordingly, the committee noted that requirements to search through, select, acquire, process, and store a wide variety of data sets to solve given problems will grow significantly. [17, p1]

The committee delineated three major types of Space Science Data Management Units (SSDMU's) as keys to meeting computation and data management challenges over the decade: data centers, data repositories, and active data base sites. They felt that explicit functional delineation of

SSDMU's, including interfaces between them, would help ensure transfer of more complete, better documented data to the centers. [17, p3]

They recommended that space science data centers (e.g., National Space Science Data Center), in coordination with their user communities, play a major role in organizing and overseeing SSDMU systems, including managing any information networks connecting the segments, providing directories and catalogs of relevant data, and stipulating standards and protocols to be used within the system. The present management structure at NASA Headquarters can be utilized to guide development and operation of distributed SSDMU systems. The Information Systems Office should manage those aspects of the systems that are of facility class in size or that transcend missions or disciplines. [17, p3]

In terms of management, the report noted that developing geographically distributed information systems involving data centers, repositories, and active data bases should be accomplished in an evolutionary fashion, and with experiments aimed at deriving the best management methods and technologies to utilize. Recognizing that NASA had some pilot activities underway, committee members recommended that these pilot information system efforts continue and expand to include other space science disciplines, but with an overall goal of moving toward implementation of distributed information systems. [17, p4]

As with the 1982 study, the 1986 report contained several technology recommendations. Among them were:

- Computation and data management capabilities must be significantly upgraded at data centers, repositories, and at active data base sites, even if just to maintain the current processing status quo.

- NASA should provide effective access to the high-speed machines at NASA centers. NASA should also continue development of software that takes advantage of the computational speed of these large, facility-class processors. NASA should also pursue investigation of low-cost concurrent processors that can be placed at local sites.

- NASA should aggressively pursue an evolutionary approach to communications networks that would interconnect the various SSDMU's that make up the coordinated, geographically distributed information systems.

- NASA should work cooperatively with the space science community in developing useful standards and protocols that can be applied to software development, system interfaces, data formats, directory/catalog formats, and documentation.

- NASA should play a leading role in developing a capability for scientists to access a distributed directory and catalog system that includes NASA and relevant non-NASA data. [17, p4-7]

9. 1987 - National Research Council Report

In 1987, the National Research Council released a report entitled, "Critical Issues in NASA Information Systems". This study was conducted at the request of NASA to identify the critical issues affecting how NASA's Office of Space Science and Applications (OSSA) should organize its information systems functions and programs to support space science and applications. [18, pv] This study differed from the earlier CODMAC studies in that it was focused on a narrower set of issues.

The study group identified four issues: centralization of management functions; interoperability; user involvement; and information system technology. For each issue area, the report provides a conclusion. For the first issue, "To what degree should information systems management and planning be further centralized?", the researchers felt that OSSA was making progress but that there was still some fragmentation and that application of centralized management would yield improvements in strategic planning, resource allocation, improve procurement and acquisition cycles, and result in a cohesive plan for creation and control of software. [18, p12]

The second issue addressed was "how can interface requirements be established that would ensure interoperability with a minimum of standards?". Here the committee recognized that OSSA was working with many dissimilar systems which vary in software languages and operating systems. However, the report recommends that NASA look toward the International Standards Organization (ISO) Open Systems Interconnect (OSI) architecture. [18, p14]

Third, "to what extent should OSSA involve its users in the development of and changes to information systems, while still maintaining control?". Here, OSSA was acknowledged for getting users involved; however, the committee found that user dialogues declined between the design phase and the development phase. [18, p15]

Finally, "how can the projected information systems technologies keep pace with future sensor outputs?". The study found areas of technological concern (e.g. planning and control of software and electronic communications of data) were only compounded for OSSA by the need to control costs (which can potentially affect OSSA's ability to support users) and the need to support the users (which influences costs). In other words, there is a trade off that must be made between the need to employ new technology and the need to live within available budgets. [18, p16] The study also provided an approximation of the daily data traffic by year that OSSA will have to handle and process. (See Table 1)

10. 1987 - Earth Science and Applications Data Systems (ESADS) Workshop Report

In May 1987, NASA released the ESADS report which related the results and plans for activities of about 90 attendees. The introduction to the report stated, "The completion of the Earth Science and Applications Data Systems (ESADS) Workshop Report is a milestone in the effort to move our heterogeneous data handling environment toward greater interoperability and greater sharing of resources. . . . The ESADS initiative was conceived as

Table 1 [18, p52]

MISSION DAILY DATA VOLUME (GIGABYTES) TIME PROFILE

Instrument	Space Vehicle	Sponsor Agency	Peak Data Rate (Mbps)	Duty Cycle P(T)	Average Data Rate (Mbps)	YEAR						
						1992	1993	1994	1995	1996	1997	1998
Audio/Video	SS	NASA	Variable	1.00	Variable	118.80	118.80	486.00	820.80	1015.20	1220.40	853.20
ASO	SS	NASA	50.00	0.67	33.33			359.96	359.96	359.96	359.96	359.96
AT	SS	NASA	3.00	0.50	1.50			16.20	16.20	16.20	16.20	16.20
STO	SS	NASA	10.00	0.25	2.50	27.00	27.00	27.00	27.00	27.00	27.00	27.00
Sensor	SS	NASA	120.00	0.15	18.00						194.40	194.40
HST	FF	NASA	1.02	0.21	0.21	2.30	2.30	2.30	2.30	2.30	2.30	2.30
LASA-B	ESA POP	NASA	1.00	0.75	0.75				8.10	8.10	8.10	8.10
SEASAR	ESA POP	NOAA	200.00	0.23	46.00				496.80	496.80	496.80	496.80
Spectr	ESA POP	Foreign	2.00	0.23	0.46							2.16
MODIS	EOS POP	NASA	5.00	1.00	5.00			54.00	54.00	54.00	54.00	54.00
MRIR	EOS POP	NOAA	21.00	1.00	21.00			226.80	226.80	226.80	226.80	226.80
VIS	EOS POP	NASA	2.00	1.00	2.00			21.60	21.60	21.60	21.60	21.60
ST(P)	EOS POP	NOAA	2.00	0.66	1.32		14.26	14.26	14.26	14.26	14.26	14.26
SAR	EOS POP	NASA	300.00	0.23	67.50					729.00	729.00	729.00
HIRIS	EOS POP	NASA	160.00	0.10	16.00			172.80	172.80	172.80	172.80	172.80
TIMS	EOS POP	NASA	29.00	0.10	2.90			32.40	32.40	32.40	32.40	32.40
AXAF	US COP	NASA	0.06	0.21	0.01		0.15	0.15	0.15	0.15	0.15	0.15
SIRTF	US COP	NASA	2.00	0.21	0.42			4.54	4.54	4.54	4.54	4.54
TOTAL DAILY DATA VOLUME (GBYTES)						148.10	162.51	1418.01	2257.71	3181.11	3580.71	3215.67
Audio/Video DATA VOLUME (GBYTES)						118.80	118.80	486.00	820.80	1015.20	1220.40	853.20
Telemetry DATA VOLUME (GBYTES)						29.30	43.71	932.01	1436.91	2165.91	2360.31	2362.47

NOTE: 1. DAILY DATA VOLUME = Average Data Rate x 3600 x 24 (Converted to Gigabytes) a management tool. It is designed to organize information from the many data systems supporting NASA Earth Science and Applications, and to use this information in generating a coordinated approach to further data system development." [28, piii]

The report detailed issues undertaken for study by various task group members. Among the issues discussed and being worked were: Directories and Catalogs; Data Archives; Data Manipulation Software; Computational Facilities; Data Storage Media; Data Base Management Systems; Networks; and Scientific and Operations Management. [28, pv] Tables 2 and 3, which follow, provide a sample of the task group's attention to detail concerning the various data storage media and efforts to analyze the advantages and disadvantages of each.

11. 1988 - The Astrophysics Data System Study

In March 1988, NASA released the final report of the Astrophysics Data Systems (ADS) Study which contains the architecture for an astrophysical data system to support reduction, distribution, and analysis of scientific data from NASA astrophysical spacecraft. The report indicates that over 60 astronomers and data system experts worked together to define user requirements for the system. [29, p 1] The study reported that work would continue to transform the ADS architecture into a program plan as the next step toward a functioning data system and that issues would be worked throughout the year with a follow-on ADS workshop to be held in November 1988. [29, p 11]

DATA STORAGE SUMMARY

Technology	Media Cost	Player Cost	<-------------Current-------------->			<-----Near Future---->		Interface	<-------Standards------->			Storage Life (years)	Maint. Period (years)
			Access Time	Transfer Rate	Capacity	Transfer Rate	Capacity		Media	Physical	Logical		
CD-ROM	$15*	$1K	1 sec	.1Mbps	550Mb	Same	Same	PC,MVAX,SCSI	Yes	Yes	Yes	30+	None
High Density Digital Tape	$200	$200K	N/A Seq. access	100Mbps	10000Mb	300Mbps	50000MB	Specialized	Some	No	No	3-5	3
Cartridge Tape	$15-$25	$12K	N/A	<1Mbps	100-200Mb	4Mbps	1000Mb	IBM M/F	Yes	No?	No	5-20	1
VHS Tape	$8		N/A Seq. access	~16Mbps	4000Mb	200Mbps	100000Mb	Dec/Prime	No	No	No	?	?
12" Worm & MO	$300	$15K	<200ms	.2Mbps	2000-3000Mb	.5Mbps	4000-6000Mb	Dec Hosts, SCSI	No	No	No	5-30	10
5-1/4" Worm&MO	$200	$25K	>200ms	.1-.2Mbps	550Mb	.3Mbps	1000Mb	SCSI,PC's,MVAX	Yes?	Yes?	No	5-30	10
Cartridge Disk	$15	$1-2K	100ms	.1Mbps	10-20Mb	.15Mbps ?	30Mb (?)	PC's	No	No	No	5	
Digital Audio Cartridge/ Cassette			Very slow	.1Mbps	550Mb ?	same	same	PC	No	No	No	?	?
Present CCT	$20	$12K	N/A Seq. access	<1Mbps	125-180Mb	same	same	Anything	Yes	Yes	Yes	5-20	1 year
Optical Tape	$200		N/A Seq. access	<.25Mbps	5000Mb	?	?	?	No	No	No	10?	?

*Cost per replica after premastering and mastering ($8k/disk).

Table 2 [28, p 33]

DATA STORAGE APPLICATIONS

Potential Applications / Media/ Hardware Type	<--Deep Archive-->		Retrievable Archive Data Level 1B	<-----CODMAC-----		----->		
					<------Discipline Working Data	------>		
	Raw Video Level 0	Data Level 1A		Distribution Data Sets RDR	Quickie Distribution Working Store	Every Day Active Analysis	Browse Image	Pros and Cons Comments
CD ROM Vendor-mastered	No	No	Maybe	Yes Moderate Data Sets, Multiple Distribution	No	No	Digital Browse, Distribution, "Digital micro-fiche"	May become a standard for distribution
High Density Digital Tape	Yes SAR, HIRIS High Volumes	Yes	Now used -- Slow access latency	No	No	No	No	Not standardized. High cost, short life.
Cartridge Tape	Yes	Yes	No	No Too specialized		No	No	Intended for juke-box. Replace regular CCT in 90's.
VHS Tape Cartridges	No	No	Maybe	Probably	Yes	Yes e.g., Workstation	Yes	
Worm & Erasable 12"	Probably	Probably	Maybe	10-copy styles	Maybe eventually	2 yrs?	Probably Not	Better host support.
Optical 5-1/4"	No too small	No	No	Yes More Universal than 12"?	Yes	Yes	Yes	Mainly workstation
Digital Audio Cartridge/ Cassette	No	No	No	Probably not	Potentially	Potentially	Potentially	Digital applications haven't evolved.
Present CCT 150-250 Mb	Used now---> Universally Useable						Don't want a serial medium	Grandfather
10-20 Mb e.g., Bernoulli Box, Kodak, etc.	No	No	No	Aplicable for modest volumes	Directly applicable but not quite readily available. Not ubiquitous.		Yes	Will need interface to big machines

Table 3 [28, p34]

IV. ISSUES

"The importance of computation and data management associated with extraction of scientific information cannot be understated. In fact, the information and knowledge extracted from space science data should be the ultimate measure of mission success." COMDAC, National Research Council, 1986. [17, p viii]

To provide a visual point of reference for the discussion of issues, Figure 8 has been included on the next page. This illustration represents the flow of data from acquisition to the user. (The illustration used in the March 25, 1988 report, "Life Cycle Cost Analysis for NASA Science Data Handling, 1988 - 2000", has been modified from its original form by the addition of a dashed vertical line delineating the division of responsibility between NASA's Office of Space Operations and Office of Space Science and Applications.)

A. ISSUE 1: Are future data flow projections realistic? If realistic, are the data requirements reasonable?

1. BACKGROUND

Given the various studies cited earlier and their differing estimates of Earth and space science data projections, questions might arise regarding the realism of these projections. Moreover, such large increases in data, if realistic, when compared to that currently processed by NASA prompts one to wonder if such requirements can be met; i.e., are they reasonable?

The initial focus of this analysis attempted to compare projections of scientific data flow to the actual data acquired, when the mission was flown. Differences did exist whenever the actual mission data was compared to very early estimates made when a project was "in the thinking stages". However, this approach to the question did not yield significant variations when actual data rates were compared to estimates made after the instrument was "on the drawing board". In fact, the review indicated that as instruments were built and investigators worked with NASA mission and project personnel, the estimates versus actual were reasonably consistent.

As a follow up to the comparison of individual project data estimates, another review was undertaken. This second avenue to identify information provided more insight. When the different report tables were compared in their entirety to determine which missions were included and the anticipated launch scenarios, differences in the range of an order of magnitude can be found. For example, in the 1987 study by the National Research Council, total daily (24 hour period) space mission data for 1995 were projected to reach 2,257.81 Gigabytes. [18, p52] Such an estimate compared favorably with current estimates by the NSSDC (NASA Space Science Data Center) which estimated data requirements for current and projected missions for 1995 to yield 2,400 Gigabytes of data per day. [25, p5]

OUR "SYSTEM"

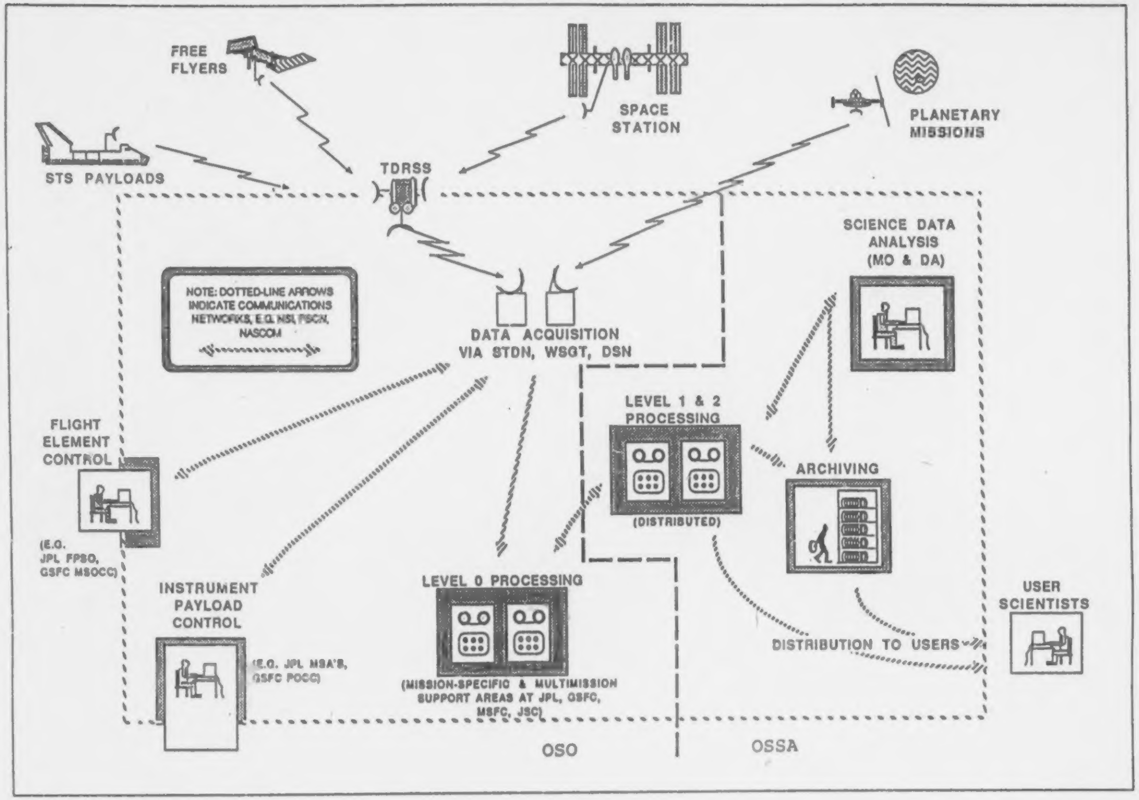

FREE FLYERS
SPACE STATION
PLANETARY MISSIONS
STS PAYLOADS
TDRSS
NOTE: DOTTED-LINE ARROWS INDICATE COMMUNICATIONS NETWORKS, E.G. NSI, PSCN, NASCOM
DATA ACQUISITION VIA STDN, WSGT, DSN
SCIENCE DATA ANALYSIS (MO & DA)
FLIGHT ELEMENT CONTROL
(E.G. JPL FPSO, GSFC MSOCC)
LEVEL 1 & 2 PROCESSING
(DISTRIBUTED)
ARCHIVING
INSTRUMENT PAYLOAD CONTROL
(E.G. JPL MSA'S, GSFC POCC)
LEVEL 0 PROCESSING
(MISSION-SPECIFIC & MULTIMISSION SUPPORT AREAS AT JPL, GSFC, MSFC, JSC)
USER SCIENTISTS
DISTRIBUTION TO USERS
OSO
OSSA

FIGURE 8 [22, p2]

(38

On the other hand, an unpublished table produced by NASA and used in preparation of the report, "Life Cycle Cost Analysis for NASA Science Data Handling, 1988 - 2000" [22], indicated a rate of 222.60 Gigabytes of data per day for 1995. These data rates were estimated based on variations in new start priorities and impacts of budget/funding changes. Thus, by the shifting of missions based on priorities and/or budgetary constraints, a difference of a factor of ten can be produced between estimates.

The idea of shifting mission traffic was further verified by comparing pre-Challenger data workload estimates to the post-Challenger era. Some earlier projections contained more mission launches and thus more total space science data traffic than the later estimates had. But again, the greatest data variation, for any point in time, was due to the number of missions rather than the individual mission estimate changing its data forecast. When even the most conservative/pessimistic forecast for 1995 science data is compared to the actual 1985 data volume of 360 Gigabytes for the entire year, NASA's 1995 workload will be nearly 225 times greater. At the other end of the spectrum, if all of NASA's approved and proposed missions are launched, workload could increase by another order of magnitude.

Assuming that NASA is aware of the possible range of its workload increase, the balance of this issue will focus on NASA's capability to process such data. Accordingly, the findings below are broken down into several sub-issues to permit a full discussion of all the processing topics.

2. FINDINGS

a. Are current projections of space science data workload realistic?

Based on the materials reviewed, the space science data projections appear to be realistic. However, it would appear that possible variations in data workload that vary by an order of magnitude would make planning difficult.

b. If we accept the space data estimates as realistic, then can NASA support the estimated workload?

(1) With all of the projected space data, will the TDRSS (Tracking Data Relay Satellite System) be able to support the requirement?

Based on materials reviewed, yes. In fact, NASA officials have testified in hearings that a configuration of 4 active TDRSS craft would be needed to satisfy the channel requirements if all of the approved and projected missions were launched. (Channels, in this context refers to the total number of space-to-Earth and Earth-to-space links or circuits that the possible number of missions in orbit at one time may require.)

Returning to actual data down linking capacity, using 2 TDRSS craft, each of the satellites can pass 400 Megabits per second (millions of bits). Thus, given 86,400 seconds per day, the 2 TDRSS craft can downlink at total of 69,120 Gigabits per day (billions of bits) or 8,640 Gigabytes per day. (Recalling from the earlier concept note that 1 byte equals 8 bits.) Understandably, this figure must be adjusted for the time that the antenna is returning to position, or slewing, after tracking a mission and for normally scheduled maintenance. Additionally, reserved capacity should be maintained for any contingency (emergency) purposes. However, even if total throughput were adjusted to reflect approximately 65% to account for these factors, 2 active TDRSS craft could satisfy a down link requirement of 5,616 Gigabytes per day, which is enough to cover even the higher mission requirements discussed earlier.

On the other hand, though 2 TDRS spacecraft could conceivably handle the volume of data traffic that will be generated by projected missions, additional in-space TDRS antennas will be required to handle the number of discrete data channels that will be generated by these missions. This latter requirement, therefore, is the one that will necessitate an eventual increase in the number of TDRS spacecraft that must be maintained on orbit.

(2) What efforts are there to ensure that processing capacity exists for future data requirements?

NASA has indicated that several efforts are underway: (a) the Customer Data and Operations System (CDOS) facility is being built to serve the space station era with: data capture, data processing, data distribution, communications, and platform and payload control; (b) the contract has been awarded for the acquisition of computer capability for Johns Hopkins University's processing of data from the Hubble Telescope; (c) the NASA Space and Earth Sciences Computing Center (NSESCC), established in 1984 by combining two existing large-scale computing facilities at the Goddard Space Flight Center provides supercomputing power [37, p1]; and (d) the completion of the second TDRSS ground terminal (STGT) and the upgrading of equipment at the White Sands ground terminal (WSGT) will provide new communications capacity for the data as it reaches Earth and is processed for further distribution.

(3) Are there other plans for meeting NASA's projected science data workload?

According to NASA, yes. One effort, the "Strategic Plan 1988", from NASA's Office of Space Science and Applications (OSSA), is specifically taking a serious look at the current trend toward large, complex, long-duration missions that by their very nature require a more deliberate pace. [34, p2]

Further, in this report the discussion of telecommunications and information systems indicates: "The information systems program has collaborated with individual research disciplines to design and build data systems for the oceans, climate, planetary, and land communities. . . . Data and information systems will continue to grow in importance as a vital support element for our scientific programs. . . . OSSA intends to evolve from the mode of designing and developing essentially independent data systems for individual flight projects and to broaden the perspective for designing systems and evaluating trade-offs that span payloads, projects, and scientific disciplines. ... The Science and Applications Information System is the basis of a strategy for planning and developing future information systems to meet the objectives of all OSSA scientific disciplines." [34, p27]

As a follow on to the overall strategy paper, OSSA initiated a new study in a memorandum on July 6, 1988 entitled, "Task Force on Information System Needs for Space Science Research of the 1990's", which stated: "The scope of the study will cover the full range of activities required to accomplish first-class scientific research including both satellite and ground systems considerations. Our intention is to examine the diverse needs of the space science research community as it performs the complete task from experiment development through retrospective analysis and to define an up-to-date approach responsive to all aspects of the scientific research process. Areas to be addressed are, flight data systems; experiment operations, including planning, scheduling and control; computer networking; computational systems; and data archival." [39, p1]

Some of the developments that have been made or are underway include:

1) At the Goddard Space Flight Center (GSFC), a system called NIMS (NSSDC Information Management System) is under development. This is a consolidation effort to pull together data storage and management at the NSSDC (National Space Science Data Center).

2) Also at the GSFC NSSDC, there is a Master Directory project now in the user evaluation phase. The Master Directory will provide top-level data location and routing to the appropriate archive for data ordering.

3) At the Jet Propulsion Laboratory (JPL), the SFOC (Space Flight Operation Control Center) is an operational effort which is receiving, processing and analyzing planetary data in near-real-time during Voyager planetary encounters.

4) JPL also has put into operation the Planetary Data System (PDS) which is a detailed specification of how to create a retrospective data handling and distribution system based on distributed data nodes and a centralized coordination and data location node. The PDS includes implementation of integration concepts such as data dictionaries, self-describing data formats, and system engineering for a distributed system.

5) The ESADS (Earth Science and Applications Data Systems) Workshops have proven fruitful according to NASA officials. This series of meetings has involved scientists and academicians with NASA personnel to find solutions to issues of mission data processing, distribution, and archiving.

6) Another recent development was the Astrophysics Data Systems Study of March 1988 which contains the proposed architecture for an astrophysical data system to support the reduction, distribution, and analysis of scientific data from NASA astrophysical spacecraft.

B. ISSUE 2: Can the scientific community analyze the flow of data envisioned?

1. BACKGROUND

Having reviewed the projections for space science data flow and touching upon some of the initiatives that NASA has undertaken to satisfy this workload, then the challenge still exists for scientists to analyze the data. This issue will review some of NASA's efforts on behalf of the scientific community as well as efforts taken by the scientists to prepare for the future. In the June 1987 report released by the National Research Council, the authors expressed the following concerns regarding the trend toward development of higher data-rate instruments: "Scientific users will have limitations on how much data they can effectively evaluate.... A careful cost-to-benefit analysis should be made before designing a data system for the high-data-rate instruments.... Some data sensors have the capability of drowning data systems with so much data that costs become unreasonable and technology may not even be able to cope with the data stream. If all data is saved, one cannot afford to extract the information that is really needed." [18, p42]

This same study further commented that the volume of space science data to be acquired would promote the use of compression algorithms to reduce data streams by one or two orders of magnitude: "Once successful algorithms are applied to the outputs of high-data-rate sensors, the resulting reduced data rates can be handled with existing technology. The development and application of data-compression techniques should be coordinated carefully with the user community, which traditionally takes the view that nobody should "mess around" with the data. They should be convinced that some trade-offs have to be made in order to maintain high throughputs over long periods of time. If the option to transmit uncompressed data over short periods of time, when needed, is maintained, the Committee believes that users can be convinced to accept compressed data." [18, p46]

2. FINDINGS

a. Is there any policy regarding space science data or any documentation used in determining what data will and should be collected?

NASA Management Instruction (NMI) 8030.3A, issued May 2, 1978, is the policy concerning data obtained from space flight investigations. Although it is currently undergoing revision, the basic tenets are expected to remain intact. The NMI policy section, 1205.101, states:

"(a) In conducting space science flight experiments, NASA shall seek to: (1) Preserve the integrity of each investigation; (2) Encourage the participation of the best qualified scientists; (3) Make the results of investigations generally available to the scientific community at the earliest practicable time; (and) (4) Document the instrument performance and probable cause of malfunctions that occur.

(b) NASA shall rely on individual scientists as Principal Investigators (PI's) to carry out a complete investigation by: (1) Selecting, when appropriate, associates known as Co-Investigators (CO-Is) who have supporting roles in the investigation; (2) Conceiving specific investigations; (3) Developing, when appropriate, the instrument for the investigation; (4) Participating actively, wherever appropriate, in the actual conduct of the investigation; (5) Reducing and analyzing the data obtained; (6) Publishing their findings as soon as practicable; (7) Making the Reduced Data Records (RDR's) and Analyzed Data Records (ADR's) along with supporting documentation available on a timely basis for use by the scientific community and the news media, in accordance with a Project Data Management Plan (PDMP); (and) (8) Documenting any significant malfunctions which occur during the lifetime of the experiment." [47, p2]

Review of the document, "Guidelines for the Development of a Project Data Management Plan (PDMP)", revealed that a PDMP addresses the activities associated with data acquired by a mission from generation of the Experiment Data Records to the delivery of the data to a specified data repository. The stated goal of a PDMP is to provide a plan that will ensure that a mission's reduced/analyzed data, with supporting documentation, will become available to the widest possible scientific community in a timely manner for as long as there is demand for the data. [23, p1] Additionally, the PDMP must also contain the policy for the discarding of Experiment and Analyzed Data Records (EDR's and ADR's) and a timeline for such disposition. [23, p12]

b. Even if the data projections seem reasonable, is there any effort to ensure that the data acquired is needed?

The PDMP is the baseline document for researchers and NASA to use in developing a mission. During the evolution of the instrument, the scientific community and NASA work to ensure that the data meets the required research objectives.

On the other hand, there does not seem to be a clear agreement between members of the scientific community interviewed for this study. Some are concerned that more data is still being requested than can be analyzed while others feel that it is better to collect as much data as possible and sort it out through computer processing and analysis.

c. What is the current status of space data from previous missions and the archiving of such data?

The National Space Science Data Center (NSSDC) at the Goddard Space Flight Center is the largest archive for processed data from NASA's space and Earth science missions. The NSSDC archives both digital and non-digital data. The digital archive is stored on approximately 120,000 magnetic tapes with the volume of over 6,000 Gigabytes. The most requested digital data sets are stored at the NSSDC (comprising about 35,000 tapes) with the remainder stored in the Federal Records Center (FRC) about 20 miles away. In addition to the digital archive, the NSSDC has a photo or film archive of over 2 million feet of film, 41,000 sheets of microfiche, and 39,000 microfilm rolls. [25, p2]

Figure 9 shows the data volumes per scientific discipline that have been archived and are expected to be archived at the NSSDC assuming both currently approved and most likely approved NASA missions are flown. According to NASA officials, the physical space that the NSSDC has to manage is nearly full, both locally and at the FRC. Thus, from the predicted amount of data to be archived, NSSDC officials realize that they must implement mechanisms to store data on higher density media and/or implement data compression techniques. [25, p3]

Some members of the scientific community have questioned whether the NSSDC in fact is an archive. The following attributes of an archive appear to be commonly envisioned by scientists using NASA data, NASA project personnel, and others involved in the processing and storage of data: (1) Archived data must be stored on a medium that has a long life; i.e., storable without rapid deterioration of data; (2) An archive requires someone to watch conditions of the facility and stored media; (3) The data stored must be on a material that permits creation of backup copies; (4) The data storage media must be capable of migrating to other media; i.e., as better technologies evolve, the data can be transitioned; (5) The archive should have equipment capable of reading the stored data; and (6) An archive has paid personnel present to provide data services to users.

As pointed out, much of NASA's space science data is stored in a repository (storage area) not in an archive. For example, user requests for data that is in the Federal Records Center (FRC) are currently filled by NASA personnel twice a month making the 20 mile trip to the FRC. Some of the stored data tapes there are in need of restoration or reproduction. However, some of the media is old 7-track tape with record density as low as 600 bpi (bits per inch) and must be read on old equipment since technology over the past couple decades has progressed to 9-track and much higher density. NSSDC efforts to restore these tapes has been slow, and at times, has required cleaning the tapes by hand to remove sticky film that occurs as the tape deteriorates. [41, p15]

Additionally, NSSDC officials have taken an inventory of space science data tapes in their possession versus the missions that have been flown. They have concluded and reported to such bodies as CODMAC (Committee on Data Management and Computation) in 1988 that some primary investigators had never returned mission data tapes. [41, p17]

Such a finding is consistent with a General Accounting Office (GAO) study, "More Emphasis Needed On Data Analysis Phase of Space Science Programs", June 27, 1977, which identified members of the scientific community who were late in returning analyzed data for NASA to store and share with other members of the scientific community. [49, pii]

In fact, a review of the "National Aeronautics and Space Act of 1958, As Amended, and Related Legislation" does not direct NASA to maintain an archive. Section 203, part (3) of the act states that NASA shall: provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof." [53, p5] However, interviews with NASA officials indicated that they do feel that maintaining mission data for future use is part of their role. And, NSSDC officials are working with the scientific community to determine which stored data

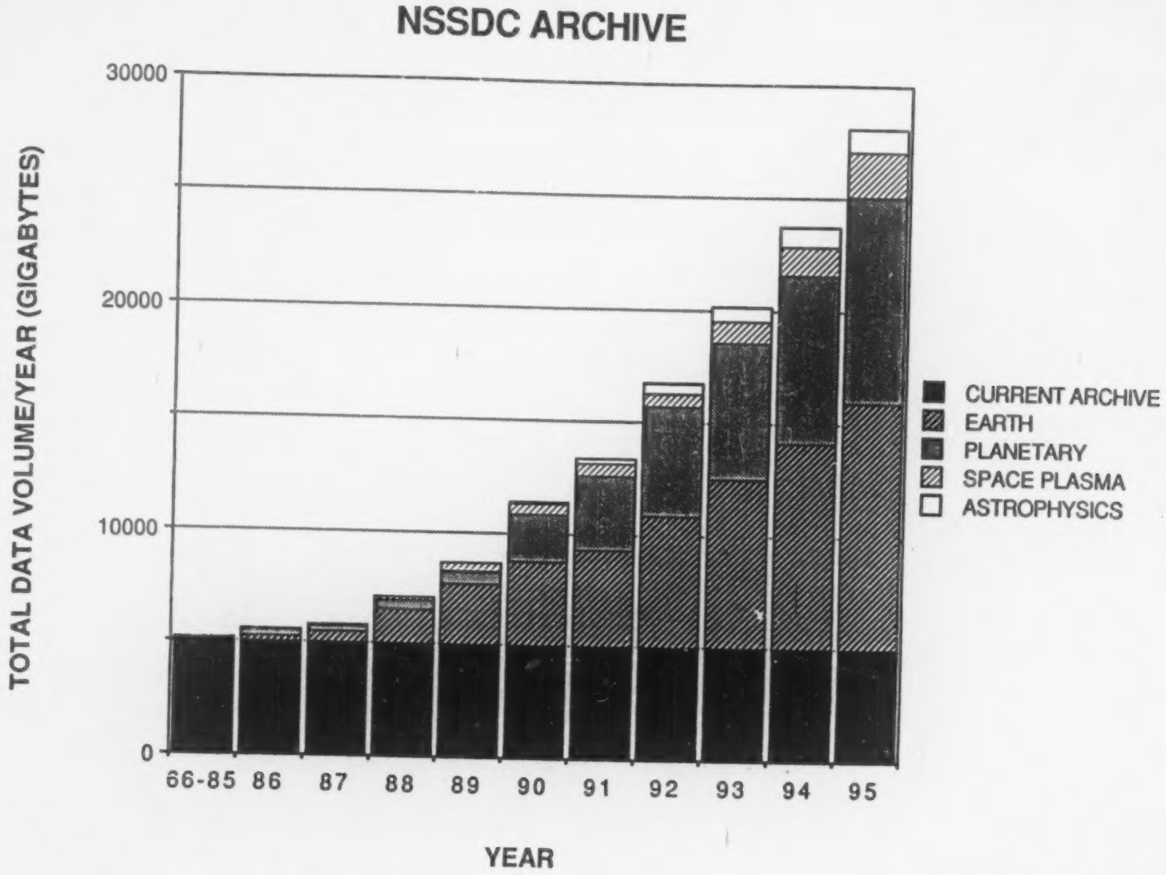


FIGURE 9 [25, p6]

tapes should be restored. In other words, some data if no longer used by scientists, should be purged rather than spending time and money to refurbish the data. Likewise, scientists are reviewing the list of missions that are missing data to determine if there is even a requirement for the data.

d. Why hasn't NSSDC been able to account for all of the data tapes for some old missions?

According to NASA officials, prior to the formation of the Information Systems Office under the Office of Space Science and Applications, the responsibility for developing the PDMP's fell into the particular office which worked with the scientist to develop the instrument. Not all projects had PDMP's written and therefore may have contributed to the NSSDC dilemma of not being able to get some old missions data. Furthermore, the NMI does not specifically detail what actions, if any, may or will be taken against a PI who does not complete the agreement in regard to the returning of data to NASA.

Many in the science community have suggested that for all future missions where a PDMP is written that failure to return the proper data to NASA should result in the imposition of a penalty. The consensus seems to indicate that NASA should not allow the violating scientist to participate in any future experiments unless the data is returned in accordance with the PDMP.

On the other hand, the 1977 report by GAO [49, pi] and members of the scientific community indicate that merely ensuring that a PDMP is written will not guarantee that the Principal Investigators (PI's) will be able to return the data in a timely fashion. They maintain that the issue centers on the funding for the data reduction and analysis. Not only do they feel funding is an issue for getting the data back to NASA for archiving but also a major factor in whether scientists will be able to analyze the greater space data workloads projected for the future.

e. What efforts are there by the National Space Science Data Center (NSSDC) to provide data for users?

Although the NSSDC is NASA's main central repository for selected data and documentation for space science flight missions, the recent development of other discipline data centers (DDC) within NASA now provides a framework for better community participation in mission data and information access. The DDC's augment the NSSDC in facilitating data access and utilization by providing an environment designed to maximize the science communities access to archived mission data products. NASA DDC's which have a formal NASA role and responsibility are: the EROS data center, Smithsonian Astrophysics Observatory (SAO), Infrared Processing and Analysis Center (IPAC), the Space Telescope Science Institute (ST-Sci), NASA Ocean Data System at JPL, NASA Climate Data System at NSSDC, and the Planetary Data System at JPL. [23, p2]

NASA has also developed a Master Directory. The Master Directory is an on-line search system located at the NSSDC that provides brief overview information about NASA, as well as important non-NASA, space and Earth science data and data information systems. More importantly, in many cases the directory offers automatic network connections to catalogs or information systems where more detailed information about data of interest may be obtained. Often, the data may be ordered through the catalogs or information systems. [23, p6]

A new effort at the NSSDC has been providing electronic access via computer networks to the directories and catalogs residing at NSSDC as well as to those residing at remote institutions. The electronic catalogs that the NSSDC maintains and supports are the NASA Climate Data System catalog, the Master Directory, the Pilot Land Data System catalog, and the Crustal Dynamics catalog. [23, p6]

f. Are there other efforts to be aware of regarding the archiving of this large volume of data?

One effort conducted by the NSSDC and the NASA Space and Earth Sciences Computing Center (NSESCC) also at Goddard has focused on providing on-line access to data gathered on the IUE (International Ultraviolet Experiment). [25, p7] In June 1988, an NSSDC official reported to the CODMAC that requests for IUE data had risen from 100 per month in 1987 to over 385 per month for the first six months of 1988. [41, p10] Using the communications networks established by NASA and the scientific communities, researchers are able to request and receive data in 2 to 15 minutes, depending upon line speeds. [41, p11]

With sufficient storage and processing capacity, on-line access to data through NASA data centers could assist data users in the future to collect the data they require for research.

Another project at NSSDC is the testing and use of various new data storage media. Among the media being tested are optical disk and compact disk (CD) ROM (Read Only Memory). One optical disk can store the equivalent data that would be contained in 20 magnetic tapes with data densities of 6250 bits per inch. Although the cost of an optical disk is roughly equal to the 20 tapes, there are advantages: 1) optical disks can be read randomly and at very high speeds; 2) a visual check of the disk, annually, can ensure that the media is still sealed; 3) optical disk readers can be connected to many devices thus allowing stored data to be read and transmitted to the user in less time; and 4) the decreased storage space required could allow archived tapes currently in the Federal Records Center to be captured on this media and stored at Goddard for more rapid transmission to the user.

According to NASA officials, future archival efforts may use a combination of advanced storage technologies and indexing and location techniques for internal data management. The Information Systems Office is tracking technology developments and assessing them not only for their performance capabilities but also for other selection criteria such as reliability, integrability, standardization and projected longevity in the marketplace. NASA's experience shows that the archival and retrieval of large data sets is quite a different function from the delivery of small parts of these data sets to individual recipients. The difference in these functions may mean different technologies for the best operation of each.

g. Does NASA have any research efforts underway to look into the problems of processing the projected volume of data?

The Center of Excellence in Space Data and Information Sciences (CESDIS), which was recently established by the University Space Research Association in collaboration with the University of Maryland under NASA sponsorship, issued a call for proposals for computer scientists to participate in a consortium of universities, industries, and government agencies to conduct research programs in computer science in support of the space and Earth science that derives from space sensor observations. [36, p2]

The CESDIS research program will concentrate on areas related to the problems of accessing and extracting information from massive and distributed data sets together with other topics in computer science that relate to NASA's space and Earth sciences programs. Both ground-based and onboard systems fall within its scope. Research areas of interest include data base system architecture, concurrent processing, expert systems, natural query languages, image recognition, information analysis, image data compression, distributed data access systems, parallel processing, and robotics and automation. [36, p3]

Many of the issues to be addressed by the CESDIS were first articulated in studies such as the Committee on Data Management and Computation (CODMAC) report, "Space Research Data Management in the National Aeronautics and Space Administration", NASA Technical Memorandum 89403, released in 1986 [51, p v-viii] and the CODMAC study, "Selected Issues in Space Science Data Management and Computation," released in 1988 [50, p4-7].

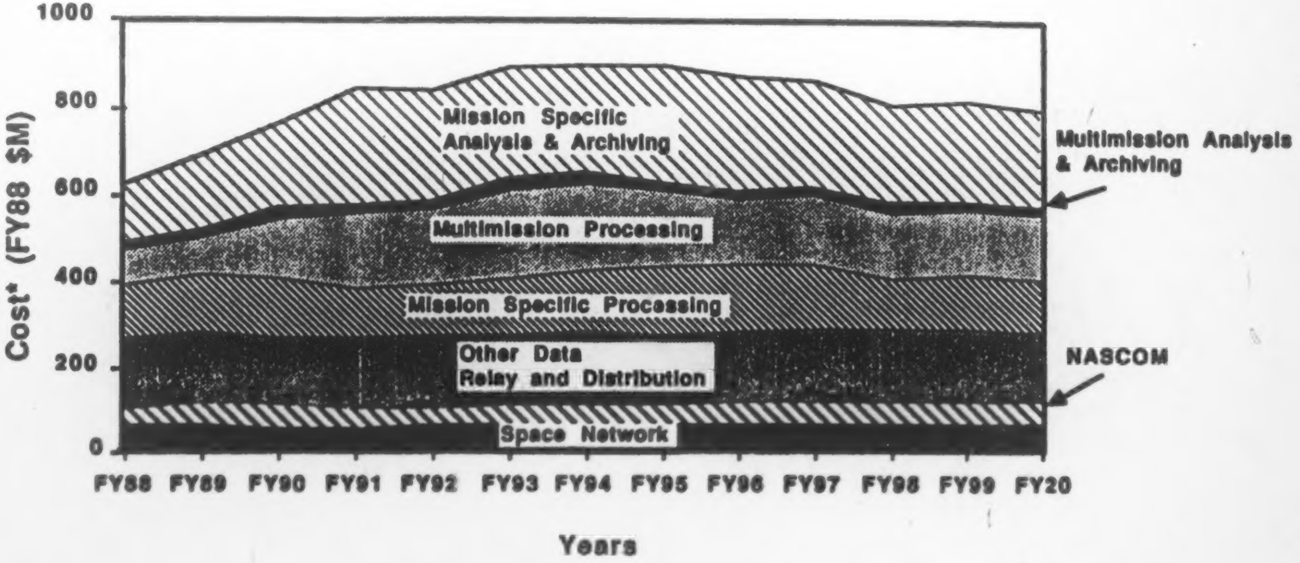
Finally, many in the science community feel confident that the greater amounts of space data can be analyzed if sufficient super-computing capacity and funding is made available.

C. ISSUE 3: Can projected funding for science data handling satisfy the workload and provide timely data to researchers?

1. BACKGROUND

In NASA's recent report to the Appropriations Committee projecting costs for science data handling through the year 2000, NASA contended that the amount of data acquired does not have a strong correlation to expenditures for analysis and archiving. [22, p17] Yet, when viewing their total life-cycle cost estimates for selected functions for approved and potential scenarios (Figure 10 and Table 4) the data appears too level.

TOTAL LIFE-CYCLE COST ESTIMATES BY FUNCTION



APPROVED + POTENTIAL SCENARIO

FIGURE 10 [22, p9]

* Costs are cumulative

APPROVED + POTENTIAL SCENARIO (FY88 $M)

FUNCTION	88	89	90	91	92	93	94	95	96	97	98	99	2000	TOTAL
SPACE NETWORK	64.8	64.8	58.6	60.3	62.0	64.7	65.0	65.0	65.0	65.0	65.0	65.0	65.0	830.2
NASCOM	43.2	51.8	50.6	41.3	45.5	46.1	47.8	49.4	50.6	52.4	53.9	55.2	56.3	644.1
OTHER DATA RELAY & DISTRIBUTION	165.1	165.6	165.2	173.6	173.3	169.2	172.6	164.9	170.2	171.9	170.0	169.5	164.5	2195.6
MISSION SPECIFIC PROCESSING	127.8	138.5	141.2	112.9	120.3	134.3	148.7	162.7	157.1	156.1	122.1	126.5	125.2	1773.4
MULTIMISSION PROCESSING	76.2	86.1	138.3	179.1	174.6	204.4	202.4	175.2	157.9	159.2	156.7	155.6	156.1	2021.8
MULTIMISSION ANALYSIS & ARCHIVING	20.2	21.3	23.5	20.5	19.8	25.6	26.2	24.6	22.6	23.7	22.5	22.0	22.3	294.8
MISSION SPECIFIC ANALYSIS & ARCHIVING	136.5	170.8	195.8	265.1	252.2	255.4	246.5	267.1	261.2	246.9	223.4	235.1	219.7	2975.7
TOTAL	633.8	698.9	773.2	852.8	847.7	899.7	909.2	908.9	884.6	875.2	813.6	828.9	809.1	10735.6

TABLE 4

However, the study clearly indicated that projecting to the year 2000 had room for error, and NASA officials detailed the areas not included within the study.

In the conclusions to its report, NASA pointed out that plans would be undertaken to strengthen the archiving of data. [22, p17] As indicated previously, NASA has started an overall review of the entire flow of data from the start of a mission to and through the archiving of the data that is collected.

Finally, the report stated that the use of new technologies envisioned in data processing and storage would help NASA hold down funding requirements, thus avoiding cost increases proportionate to the increased data flow.

The Congressional Budget Office report, "The NASA Program in the 1990s and Beyond", released May 1988, also contains a projection for NASA's programs as currently envisioned (core program). These numbers (Figure 11 and Table 5) also appear relatively level. However, the authors of this study indicate that: "If NASA is to carry out the program it has envisioned... then additional increases in funding will be required through the remainder of the century." [33, pix]

2. FINDINGS

a. What are some of the necessary expenditures not in these studies that would increase future budgets?

NASA's report was clear that certain expenditures were not included in the report. However, to envision the potential costs for collection of space science data, the following items might be factored into the equation: 1) advanced TDRSS craft and the costs of launching; 2) increased computing resources; 3) the additional communications lines to carry the traffic; 4) any costs for improving the existing archives and helping NASA bring existing records up to archive quality before the increased flow of new data begins to arrive; and 5) NASA may need to increase expenditures for data analysis to ensure that mission data is reviewed, published, and archived on a more timely basis.

b. Has NASA taken any steps to control costs?

NASA has taken some steps to ensure that its communications networks are properly sized. For instance, with the PSCN, one year after being declared as an operational network in March 1986, user requests for high data rate tail circuits (communications lines to their sites from the PSCN) were increasing rapidly. A NASA review of circuit requests indicated that a significant number of requested 56 kbps (kilo bits per second) circuits could be dropped to 9.6 kbps. Such drops in communications requirements mean significant savings in monthly circuit lease charges.

NASA Budget: Historical and Projected (the "Core Program")

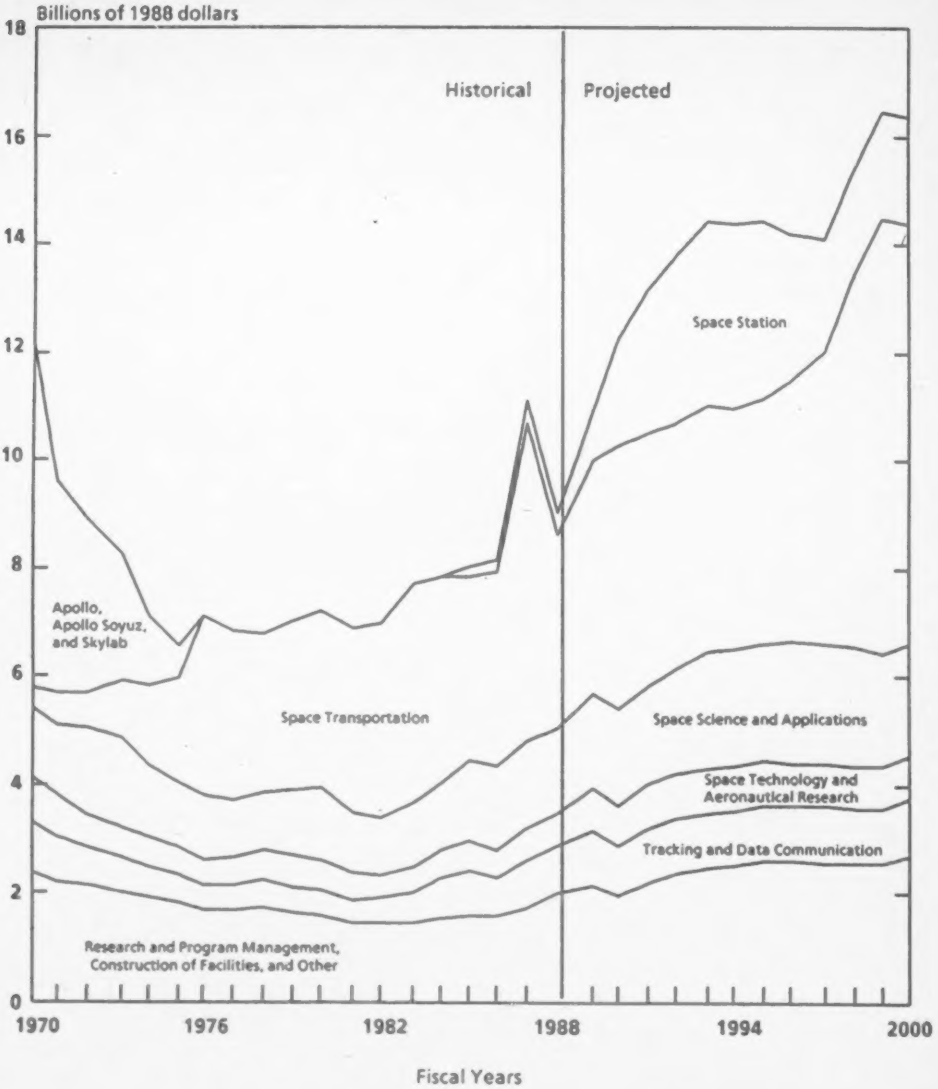


FIGURE 11 [33, p xii]

SOURCES: Historical data, NASA budget plans as presented in *NASA Budget Estimates* for various years, and Congressional Budget Office projections.

CORE PROGRAM MAJOR COMPONENTS AND ANNUAL BUDGET AUTHORITY 1987 THROUGH 2000
(MILLIONS OF 1988 DOLLARS)

	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Space Transportation	5867	3589	4300	4845	4710	4545	4570	4430	4525	4825	5435	6895	8005	7755
Tracking and Data Communications	871	884	984	930	1010	1010	1010	1010	1010	1010	1010	1010	1010	1010
Space Station	433	392	920	1980	2660	3100	3400	3415	3265	2680	2070	1915	1975	1975
Space Science and Applications	1595	1575	1762	1715	1780	1905	2135	2180	2200	2230	2180	2160	2060	2060
Commercical Programs and Technology Utilization	42	74	55	55	55	55	55	55	55	55	55	55	55	55
Space Technology and Aeronatical Research	598.	558	766	810	810	810	800	800	800	800	800	800	800	800
Safety, Reliablilty and Quality Assurance	12	14	21	20	20	20	20	20	20	20	20	20	20	20
Tracking and Data Advanced Systems	18	18	18	20	20	20	20	20	20	20	20	20	20	20
Construction of Facilities	174	178	271	250	250	250	250	250	250	250	250	250	250	250
Research and Program Management	1451	1743	1822	1630	1870	2065	2155	2205	2280	2270	2265	2230	2225	2390
TOTAL	11062 11062	9026 9026	10918 10918	12255 12257	13185 13184	13780 13775	14415 14419	14385 14384	14425 14427	14160 14158	14105 14102	15355 15356	16420 16417	16335 16334

TABLE 5

c. If users paid more for data would they moderate their data requirements?

Any thought of charging for space data should have as its objective to eliminate unnecessary requirements, but not to stifle or discourage users from getting and using data. Many of NASA's activities work on a materials only basis, especially the archives. Even with this system, requests for large amounts of data seem to be modulated. Some people interviewed feel the issue bears further review by NASA. However, others point out that there can be adverse impacts from charge-back systems. One aspect, often overlooked, is the added administrative costs for collecting the charges.

d. Are there changes needed in the manner that NASA funds space science data reduction and analysis?

Most members of the scientific community expressed a desire to see the account called, Missions Operations and Data Analysis, separated and funded so that resources were available to ensure enough funding to properly complete the computer processing of data, analysis, publication of findings, and return of data to NASA for archiving. Likewise, many of these same individuals felt that further funding would be needed if NASA were to develop a good archiving system and to play "catchup" with the restoration of old data tapes and to purge old records no longer needed.

At the same time, some of those interviewed felt that if the scientific community were more closely involved in planning the entire mission and had a better appreciation of the costs of processing data that some data requirements might be scaled down.

D. ISSUE 4: Is the second TDRSS (Tracking and Data Relay Satellite System) ground terminal (STGT) needed? Will a third terminal be required later?

1. FINDINGS:

a. Why a second terminal?

NASA officials have stated that the STGT is needed to: 1) eliminate the TDRSS White Sands Ground Terminal (WSGT) as a single point of failure; and 2) extend flexible, reliable space network support capability through the end of the century by supporting the increased data rates that are projected. [11, p338]

b. What does the expression "single point of failure" mean when related to the existing ground station?

The current ground terminal has no backup facility. Thus, a major fire or equipment failure would cause an extended outage to the entire TDRSS network. Such an outage would virtually eliminate space/Earth and Earth/space communications for earth orbit missions except for some communications that could use the STDN (Spaceflight Tracking and Data Network).

c. What added flexibility will a second ground terminal give?

In 1987, NASA officials reiterated that when the space station is operational a constraint for tracking will be the number of antennas in orbit. Therefore, NASA plans to put four craft into orbit. [12, p167-168] Accordingly, there must be adequate ground facilities to satisfy the downloading of data from a four active craft constellation.

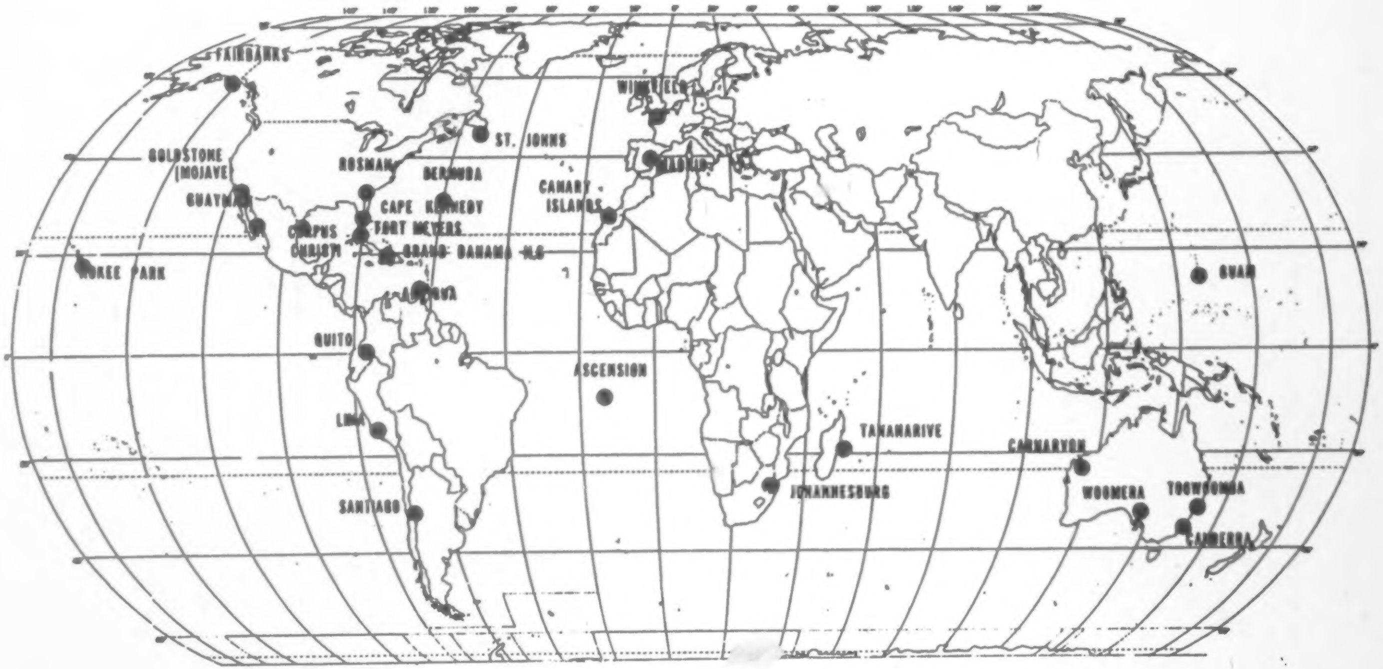
According to NASA officials, based on NASA's current budget plan, the STGT and WSGT upgrade implementations will be completed before the Space Station becomes operational and four on-orbit TDRS operations is required. Since each ground terminal will have two independent and fully redundant equipment elements capable of supporting two on-orbit TDRS, the space network will fail soft. The probability of having an extended outage due to a major hardware failure with these new ground terminal systems is considered to be very small relative to the existing ground terminal design. Accordingly, the modular design of each TDRS support element may localize the damage caused by a major fire to one TDRS support element. The three remaining TDRS support elements would still permit operation of three satellites, which provides the six on-orbit single access antennas required in the Space Station era. If a major fire caused the loss of both TDRS support elements at one ground terminal, the other ground terminal could continue to provide the support required to maintain the health and safety, with reduced science support, for all unmanned spacecraft while continuing to provide the necessary support requirements for Space Shuttle and Space Station missions.

d. Why not use the STDN (Spaceflight Tracking and Data Network) rather than build the STGT?

The STDN provided very good support in its time. However, as Figure 12 graphically shows, there were many ground stations needed in 1968, and with all of these ground station, they could only support approximately 15% of a craft's Earth orbit. Since implementing the TDRSS, NASA has been able to steadily reduce the number of STDN sites to better control costs.

In order to provide the added coverage needed, the STDN would have to undergo several changes. First, the ground network have to be rebuilt beyond its former size in 1968 to yield the mission coverage required. Second, new equipment would be needed to facilitate the range of data rates and frequencies that are passed over the TDRSS. Third, in conjunction with the expansion of sites worldwide, NASA would be required to find communications assets in foreign countries that are more easily found within the United States. Forth, in order for NASA to expand the number of ground network sites, agreements with foreign countries would be needed, and even if successful, such a move would have a negative impact on the balance of payments since historically much of the operational cost for a ground station goes for salaries to the foreign nationals that operate the sites. Finally, operational problems would exist since a mission craft would be required to vary its communications of data from an orbiting TDRS craft to a ground site.

1968 NASA TRACKING & DATA ACQUISITION STATIONS


FAIRBANKS
GOLDSTONE (MOJAVE)
GUAYMAS
CORPUS CHRISTI
ROSMAN
BERMUDA
CAPE KENNEDY
FORT MEYERS
GRAND BAHAMA IS.
ANTIGUA
ST. JOHNS
KOKEE PARK
QUITO
LIMA
SANTIAGO
CANARY ISLANDS
WINKFIELD
MADRID
ASCENSION
TANANARIVE
JOHANNESBURG
CARNARVON
WOOMERA
TOOWOOMBA
CANBERRA
GUAM

NASA HQ TA65-15917
REV. 7-23-68

FIGURE 12

e. If a second TDRSS ground terminal is required, why wasn't it in the original plans?

Plans for a second TDRSS ground terminal were not in the initial TDRSS concept as presented to Congress. Yet, as early as 1980, NASA officials did recognize that new computers would be needed at the WSGT. Accordingly, they became aware that the future replacement or upgrading of computer equipment (hardware) once the TDRSS was operational would require some backup facility. [8, p399]

f. Why 3 miles away? Wouldn't a greater distance help to preclude a natural disaster such as a storm that would block both terminals?

During the 1987 NASA Authorization Hearings, NASA stated that it had selected a site about 3 miles from the present ground station. [11, p328] When asked why so close, NASA officials responded that they had done a site survey for the whole area within the antenna pattern of the present location. They found two acceptable sites. The other one was about 150 miles away. It was determined that over a 10-year period NASA could save approximately $75 million in operating costs (logistics, personnel, etc.) by locating the second ground terminal in the same general area as the present ground station. In addition, NASA felt that a distance of 3 miles would provide sufficient separation so that a single heavy rain storm could not adversely effect both ground stations simultaneously. [11, p328]

An analysis of WSGT downtime/outage reports disclosed that on only two occasions had the terminal been down for weather related conditions. The first occurred during the Winter of 1983 for 8 hours because of icing conditions. After that incident, NASA modified the antennas with deicers. The second down time was in the Fall of 1987 for one-half of an hour for rain. [46, p1] Prior to completing this study, NASA officials reported that on July 9, 1988, rain caused a one-half hour loss for the WSGT but only for MA (Multiple access) service.

Moreover, NASA indicates that, during the survey to select a site, contact was made with the New Mexico State Meteorologist to ascertain information on area thunderstorm cells. The conclusion was that storms as large as 3 miles are rare, occurring with a frequency of roughly 2 days per year. Heights for such storms of 35,000 to 40,0000 feet are typical, but 45,000 feet (the height required to block signals) are quite rare, occurring with a frequency of at most 1 day per year. [45, p2] Additionally, a second survey document containing a series of recommendations on how to best support a four TDRSS craft configuration, showed further analysis that a space to ground link (SGL) outage at both sites would be unlikely. [46, p4-5] Based on actual experience compiled at the WSGT since start-up and the weather of that area, it is possible that the probability of simultaneously outing both stations at 3 miles apart would be no greater than would apply if a second station were located nearly two hundred miles away (the limit of the antenna pattern).

g. Would a further spacing between the TDRSS terminals have helped to reduce the Zone of Exclusion (ZOE)?

The ZOE, which is the communications gap over the Indian Ocean that can be as much as 15% of an orbit, could be eliminated if a ground station were placed in Hawaii and if the orbiting TDRSS craft were placed further apart.

A NASA study conducted in 1978 concluded that although the ZOE could be eliminated, the positioning of the TDRSS spacecraft would have to be modified. With the shifting of the craft, the existing WSGT and the second terminal would be isolated in their support of east and west TDRSS craft. Consequently, both ground terminals would require added redundancy to preclude service outages. Moreover, this effort would be costly, and given the TDRSS ground terminal at White Sands was covering 85-100% of a craft's orbit, unwarranted.

h. What role would a second ground terminal have?

The need for the STGT goes beyond a simple backup role. The projected number and complexity of missions, including the space station, coupled with the need to provide 85 to 100% orbit coverage dictate that there be capacity added. The deployment of a configuration with four operating TDRS craft requires that a second ground terminal be built.

Furthermore, the WSGT is eleven years old (making it difficult to obtain replacement parts when they are needed) and much of the current hardware needs to be reconfigured to correct for conceptual design deficiencies that have become apparent since the ground station has been in operation. By completing a second terminal by 1992, the WSGT can be shut down to permit installation of new equipment and brought back into operation before the data requirements from the Space Station and several other missions materialize. The WSGT upgrade (or retrofit) will improve WSGT's capability by providing processing redundancies not currently present. After the upgrade of the WSGT is completed, the STGT will continue to provide protection against catastrophic failures.

NASA's analysis of the current WSGT related to user support availability for two TDRS operations indicates that the terminal could be down 15% of the time. NASA has closely monitored WSGT operations during the past two years in preparation for the next TDRS launch. This data has indicated that specific user services could be down or not available for user support more than 15% of the time and that the average ability of all the user services is approximately 85-90%. These outages or service availability statistics, which are due to a large backlog of hardware in the maintenance depot, are generally viewed as unacceptable. An intensive training program was initiated 18 months ago to increase the skill levels of the maintenance personnel and to improve the user support availability for two TDRS operations. These statistics do not include scheduled down time for maintenance, modifications, and software deliveries; on-orbit TDRS problems that cause service outages; or for weather outages.

The major concern for two TDRS operations is the contractor's ability to maintain the user service equipment in the existing WSGT because it is very complex, hard to fault isolate, and the absence of complete redundancy due to the station architecture.

A simple and rough sketch of the new ground terminal configuration, Figure 13, shows the current WSGT as compared to the STGT as planned. The STGT will have dual processing capability on independent systems -- processors (computers) will be provided for each antenna's data. Thus, the failure of one system will not negate the station's ability to send and receive data. Again, upon completion of the STGT, NASA will upgrade the WSGT to the same configuration.

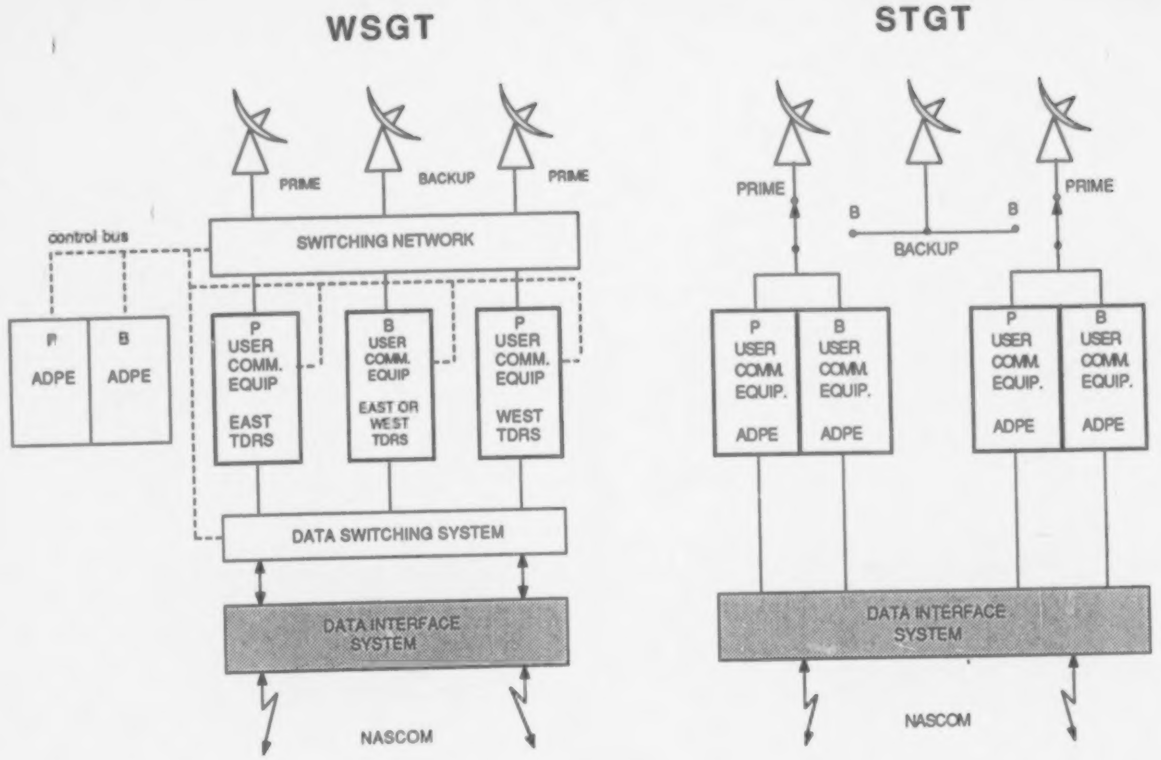
In other words, the Second TDRS Ground Terminal (STGT) architecture (reference Figure 13) provides 100 percent hardware redundancy in each of the two TDRS support elements. Each TDRS support element has separate and independently controlled communications and data processing equipment. This fully redundant modular design approach, which is similar to the STDN design, will significantly improve the reliability, maintainability, and availability of the STGT TDRS support elements relative to the WSGT support elements. Future STGT modifications or changes such as those for ATDRSS (Advanced Tracking Data Relay Satellite System) or replacement of obsolete equipment, can be implemented cost effectively without interfering with ongoing user support due to the modular redundant design of the STGT support elements. Due to the WSGT architecture, which includes a centralized computer system to control complex switching systems that are required to share the limited hardware resources, cost effective modifications or equipment replacements cannot be implemented without major impacts to ongoing user support.

After the STGT becomes operational, the WSGT will be upgraded with equipment and with a systems architecture identical to the STGT. Upon completion of the upgrade, both ground terminals will have the same support capability and each can provide reliable backup to the other in case of an extended outage due to a major fire or equipment failure. The probability of a major equipment outage after the WSGT upgrade will be significantly reduced because both stations will have the STGT architecture which includes full redundancy for ALL TDRSS spacecraft and user support elements.

When the Space Station becomes operational, additional TDRS single access antennas in orbit will be required to support the added workload. Based on current space network loading studies, six operational TDRS single access antennas will be required to provide support for Space Station and all other TDRSS users through the year 2000. NASA plans to provide this support with four TDRS spacecraft on orbit, two in the east and west TDRS locations, which provides one spare single access antenna in each location. The full support capability of both ground terminals (WSGT and STGT) will be required to support four TDRS on orbit.

i. What factors favor the 3 mile proximity of a second ground terminal for the TDRSS?

By being separated by approximately 3 miles, the two sites will be able to share operations and maintenance personnel, and avoid duplication of overheads such as administrative personnel. Estimates of total staffing


WSGT
STGT
PRIME
BACKUP
PRIME
control bus
SWITCHING NETWORK
P ADPE
B ADPE
P USER COMM. EQUIP EAST TDRS
B USER COMM. EQUIP EAST OR WEST TDRS
P USER COMM. EQUIP WEST TDRS
DATA SWITCHING SYSTEM
DATA INTERFACE SYSTEM
NASCOM
PRIME
B
BACKUP
B
PRIME
P USER COMM. EQUIP. ADPE
B USER COMM. EQUIP. ADPE
P USER COMM. EQUIP. ADPE
B USER COMM. EQUIP. ADPE
DATA INTERFACE SYSTEM
NASCOM

TDRSS GROUND TERMINALS - FUNCTIONAL DIAGRAM

FIGURE 13

vary; however, the most reasonable figures seem to indicate that where WSGT employs approximately 350 people, the two sites will require approximately 400 people. This staff sharing was part of NASA's analysis which concluded that the 3 mile distance could save nearly $75 million over a ten-year period.

j. If there are economies to be gained from placing the second TDRSS terminal near the WSGT, then why not just expand the WSGT building to house all the equipment needed?

Separation of the two facilities is required for several reasons: 1) the requirement to support a TDRS located between 38 and 45 degrees west longitude for future four TDRS operations which cannot be supported from the current site location due to blockage by the mountains to the southeast, 2) a separation of more than two miles was required because the local heavy rain cells and thunder storms that cause service degradation and outages are usually limited to 1 1/4 miles in diameter, and 3) added security in case of a catastrophic accident. In addition, the only usable locations available for the additional 60 foot antennas near the current building would at best provide marginal backup service for a TDRS located at 41 degrees west longitude due to blockage by the mountains to the southeast.

Expanding the existing building with the 60 foot antennas remotely located with wideband microwave systems interconnecting the antennas with the equipment was considered. However, the cost of implementing and maintaining the microwave system far out weighed the cost savings for expanding the existing building.

The STGT site is three miles north of the existing site and located at the only place on the White Sands Test Facility where there is a deep valley in the mountains to the southeast that will permit reliable operations for the east TDRS.

SUB ISSUE: Will a third ground terminal be required?

a. If the second TDRSS ground terminal (STGT) will be used to support the 4 TDRS craft configuration, then will sufficient backup capacity for the two sites exist?

The proposed use of separated processors (Figure 13) within the two ground terminals will provide the capability for support of the 4 craft without another terminal.

According to NASA, a third ground terminal is not required to support the current NASA mission model through the year 2000. This model can be supported with a four on-orbit operational TDRS configuration with the STGT and the upgraded WSGT because each ground terminal will have two independent and fully redundant TDRS support elements. The four on-orbit TDRS configuration has built in backup because eight single access antennas are available for support and only six, three in the east and three in the west locations, are required to support the mission model. The ground terminal backup is built-in because of the independent and fully redundant design of the TDRS on orbit support elements. Each element includes all of the processors and communications equipment required to support a TDRS spacecraft and its user satellites.

b. Will the two TDRSS ground terminals need to be changed to support advanced TDRS craft in the year 2000?

Modifications will be required to accommodate the increased data rate requirements currently planned for the advanced TDRS spacecraft. NASA is actively pursuing an advanced TDRS configuration that will minimize the impacts to the White Sands Ground Terminals. The modular architecture of the upgraded WSGT and STGT facilities will permit cost effective changes and/or additions to each ground terminal while continuing to provide ongoing support to user spacecraft. These changes and/or additions must be implemented and certified operational at least one year before launch of the first advanced TDRS to support spacecraft compatibility and prelaunch testing. Such modifications will likely be undertaken in an evolutionary way as the system will be operating with both the current and advanced spacecraft over an extended period.

BIBLIOGRAPHY

1. U.S. Congress. House of Representatives. Committee on Science and Technology. Subcommittee on Space Science and Applications. 1984 NASA Authorization Hearings. 98th Congress, 1st session, February 3,8,10,22,23,24,25,26,28; March 1,2,3, 1983. Washington, D.C. U.S. Government Printing Office, pp 181-211.

2. U.S. General Accounting Office. "Space Operations - NASA's Use of Information Technology." Report to the Chairman, Committee on Science, Space and Technology. April, 1987. GAO/IMTEC-87-20.

3. "NASA's MIS Crashes", Information Week, March 21, 1988. Issue 161, pp 8-10. by Stapleton and Puttre.

4. U.S. Congress. House of Representatives. Committee on Science and Technology. Subcommittee on Space Science and Applications. United States Civilian Space Programs 1958-1978. 97th Cong., 1st sess. Washington, D.C. U.S. Government Printing Office. Vol I, Serial D, January 1981. pp116-142.

5. U.S. Congress. House of Representatives. Committee on Science and Technology. Subcommittee on Space Science and Applications. United States Civilian Space Programs, Volume II: Applications Satellites. 98th Cong., 1st sess. Washington, D.C. U.S. Government Printing Office. Serial M, May 1983. pp367-381.

6. U.S. Congress. House of Representatives. Committee on Science and Technology. Subcommittee on Space Science and Applications. 1977 NASA Authorization Hearings. 94th Cong., 1st & 2d sess. October 13,14,15,16,& 17; November 6,11,12,13,& 18, 1975. Washington, D.C. U.S. Government Printing Office. Vol I, Part 1. pp790-813.

7. U.S. Congress. House of Representatives. Committee on Science and Technology. Subcommittee on Space Science and Applications. 1981 NASA Authorization (Program Review). 96th Cong., 1st sess. October 16,17,18, 1979. Washington, D.C. U.S. Government Printing Office. Vol I, pp352-357.

8. U.S. Congress. House of Representatives. Committee on Science and Technology. Subcommittee on Space Science and Applications. 1982 NASA Authorization (Program Review). 96th Cong., 2d sess. September 16,17,18, 1980. Washington, D.C. U.S. Government Printing Office. Vol II, pp391-419.

9. U.S. Congress. House of Representatives. Committee on Science and Technology. Subcommittee on Space Science and Applications. NASA'S Five-Year Plan, Hearings. 98th Cong., 1st sess. July 26,28, 1983. Washington, D.C. U.S. Government Printing Office. pp112-143.

10. U.S. Congress. House of Representatives. Committee on Science and Technology. Subcommittee on Space Science and Applications. NASA's Long Range Plans, Hearings. 99th Cong., 1st sess. September 17,19, 1985. Washington, D.C. U.S. Government Printing Office.

11. U.S. Congress. House of Representatives. Committee on Science and Technology. Subcommittee on Space Science and Applications. 1987 NASA Authorization, Hearings. 99th Cong., 2nd sess. February 25, 27; March 11, 13, 20; April 9, 10, 1986. Washington, D.C. U.S. Government Printing Office. Vol II, pp 277-354.

12. U.S. Congress. House of Representatives. Committee on Science, Space, and Technology. Subcommittee on Space Science and Applications. 1988 NASA Authorization, Hearings. 100th Cong., 1st sess. February 5,24,25; March 3,5,10,11,18,19,31; April 23; May 6, 1987. Washington, D.C. U.S. Government Printing Office. Vol II, pp162-225.

13. "Remote Sensing - Handling the Data", Space, March-April 1987. Vol 3, Number 1. pp8-11. by Sloggett & Williams.

14. U.S. General Accounting Office. "Budget Reimbursements - The National Aeronautics and Space Administration's Reimbursable Work." Report to the Chairman, Committee on Science, Space and Technology. June 1987.

15. NASA, National Aeronautics and Space Administration. 1986 Long-Range Program Plan. August 1985. Washington, D.C.

16. "Data Management and Computation, Volume 1: Issues and Recommendations", Committee on Data Management and Computation; National Research Council, National Academy Press, 1982. Washington, D.C.

17. "Issues and Recommendations Associated with Distributed Computation and Data Management Systems for the Space Sciences", Committee on Data Management and Computation; National Research Council, National Academy Press, 1986. Washington, D.C.

18. "Critical Issues in NASA Information Systems, Final Report to the National Aeronautics and Space Administration", the Committee on NASA Information Systems, Board on Telecommunications-Computer Applications, Commission on Engineering and Technical Systems, National Research Council, National Academy Press, June 1987. Washington, D.C.

19. "Space Network, TDRSS Data Book", TDRSS Program Division, Code TX, NASA Headquarters, Washington, D.C. April 1985.

20. "Policy Challenges Facing the U.S. Space Research Program", Physics Today, May 1988, Vol 41, No 5, pp 78-83. by Lanzerotti and Rosendhal.

21. "Mission Requirements and Data Systems Support Forecast", STDN No.803, June/July 1988, NASA, Goddard Space Flight Center, Code 501.

22. "Life Cycle Cost Analysis for NASA Science Data Handling, 1988 - 2000", A Report to the HUD - Independent Agencies Subcommittee of the Committee on Appropriations of the United States Senate. March 25, 1988. NASA.

23. "Guidelines for the Development of a Project Data Management Plan (PDMP)", Draft, James L. Green and Joseph H. King, National Space Science Data Center, NASA/Goddard Space Flight Center. April 1988.

24. "OSSA Information Systems", Briefing Presentation to the International Forum on Scientific Uses of the Space Station. Joseph H. Bredekamp, Communications & Information Systems Division, Office of Space Science and Applications, NASA, 17 May 1988.

25. "Space Data Management at the NSSDC: Applications of Data Compression", Presentation to Scientific Data Compression Workshop. James L. Green, National Space Science Data Center, NASA, May 1988.

26. "A Cost Effectiveness Analysis of the NASA Tracking and Data Relay Satellite System (TDRSS)". S. Wolf, J. Kirkland, R. Kupersmith, Operations Research, Inc., Technical Report No. 1131. 2 March 1977.

27. "Planetary Data System, A New Dimension in Planetary Data Analysis". NASA. Pamphlet. Undated.

28. "Earth Science and Applications Data Systems Workshop". Workshop Report. NASA. May 1987.

29. "Astrophysics Data Systems Study". Final Report. NASA. March 1988.

30. "OSSA Information Systems Mission". Briefing Slides, Joseph H. Bredekamp, Communications & Information Systems Division, Office of Space Science and Applications, NASA, 6 June 1988.

31. "NSESCC, NASA Space and Earth Science Computing Center". NASA. Pamphlet. Undated.

32. "New Interagency Working Group on Data Management for Global Change." Paper, provided by NASA. November 30, 1987.

33. U.S. Congress. Congressional Budget Office. The NASA Program in the 1990s and Beyond. May 1988.

34. "Strategic Plan 1988", NASA. Office of Space Science and Applications. April 6, 1988.

35. NASA Ltr., "Reimbursement Rates for CY 1989 for TDRSS Services," June 24, 1988.

36. NASA. "Center of Excellence in Space Data and Information Sciences (CESDIS)," Call for Proposals. Undated.

37. NASA. "NASA Space and Earth Sciences Computing Center (NSESCC)," brochure. Undated.

38. "Data Compression Experiments with LANDSAT Thematic Mapper and NIMBUS-7 Coastal Zone Color Scanner Data," James C. Tilton and H. K. Ramapriyan. Presentation to Scientific Data Compression Workshop, Snowbird, Utah. May 3-5, 1988.

39. NASA. Memo. "Task Force on Information System Needs for Space Science Research of the 1990's," Code EC. June 20, 1988.

40. "National Space Science Data Center," Briefing by James L. Green. Presentation to Dr. Fletcher. January 1988.

41. "NSSDC Review," Briefing. Presentation to CODMAC. June 1988.

42. "NSSDC Report to CODMAC," Draft. NASA. Code 633. June 16, 1988.

43. "The Space Physics Analysis Network," James L. Green, North- Holland Physics Publishing Division, North-Holland, Amsterdam. 1988. pg 205-213.

44. "Geometric Analysis of STGT/WSGT SGL Beam Aspects with Regard to Storm Cells," Stanford Telecommunications Inc. McLean, VA. 30 September 1985.

45. "WSTF Storm Cell Impact Assessment for Collocated TDRSS Ground Terminals," NASA. Briefing. Code 530, STGT Project Manager. 10 December 1985.

46. "WSGT Outages," NASA. Report. October 1, 1987.

47. "Policy Concerning Data Obtained from Space Flight Investigations," NASA. NASA Management Instruction (NMI) 8030.3A, May 2, 1978.

48. "NASA", Government Computer News. Special Profile section. Vol 7, Number 12. June 10, 1988. 40 pages.

49. U.S. General Accounting Office. "More Emphasis Needed on Data Analysis Phase of Space Science Program, National Aeronautics and Space Administration." Report to the Congress. June 27, 1977. PSAD-77-114.

50. "Selected Issues in Space Science Data Management and Computation." Committee on Data Management and Computation. National Research Council. National Academy Press. 1988. Washington, D.C.

51. NASA Technical Memorandum 89403. "Space Research Data Management in the National Aeronautics and Space Administration." George H. Ludwig. CODMAC. 1986.

52. "International Space Effort to Assess Earth's Environment." Aviation Week & Space Technology. August 22, 1988. McGraw-Hill. Reporter: Craig Covault.

53. "National Aeronautics and Space Act of 1958, As Amended, and Related Legislation." December 1978. U.S. Government Printing Office. Washington, D.C.

APPENDIX

GLOSSARY OF TERMS

Term	Explanation
A/C	Air Conditioning
A/D	Analog to Digital (Converter)
Access	To locate the desired data.
Acronym	A word formed from the first letter(s) of the words contained in a phrase or name.
ADPE	Automatic Data Processing Equipment
AFSCF	Air Force Satellite Control Facility
AM	Amplitude Modulation
Amplitude	Magnitude or size. The maximum departure of the value of a wave or alternating current from its average value.
Analog	Referring or pertaining to a signaling technique in which a transmission is conveyed by modulating (varying) the frequency, amplitude, or phase of a carrier. An analog signal is typified by a continuous wavelike pattern.
Analog Transmission	Transmission of a continuously variable signal as opposed to a discretely variable signal. Physical quantities such as temperature are continuously variable and so are described as "analog".
Architecture	The organization and interconnection of computer system components.
ARPA	Advanced Research Projects Agency of the U.S. Department of Defense, which supports the ARPANET resource-sharing computer network.
Backup	Alternate programs or equipment used in case the original is incapacitated.
Bandwidth	The difference in cycles per second, or hertz, between the high and low frequencies of a band.
Baud	Unit of signaling speed. The speed in bauds is the number of discrete conditions or signal elements per second.
Bit	Contraction of "binary digit", the smallest unit of information in a binary system. A bit represents the choice between a mark or space (one or zero) condition.
Bit Rate	The speed at which bits are transmitted, usually expressed in bits per second.

BPI	Bits per inch
bps, b/s	Bits per Second
Byte	A small group of bits of data that is handled as a unit. In most cases it is an 8-bit byte.
C-band	3700 to 6500 Mhz
CCITT	International Telegraph and Telephone Consultative Committee. A group within the International Telecommunications Union (ITU) that recommends data communications standards.
CD	Compact Disk
CDHF	Central Data Handling Facility
Channel	In data communications, a one-way path along which signals can be sent between two or more points. Also called circuit, line, link, or path.
Circuit	A two-way path along which signals can be sent between two or more points.
CODMAC	Committee on Data Management and Computation (NRC)
Comsat	Communications Satellite Corporation, a private U.S. company established by statute as the exclusive international satellite carrier and representing the U.S. in Intelsat.
CPU	Central Processing Unit
DBMS	Data Base Management System
Digital Signal	A discrete or discontinuous signal; on whose various states are discrete intervals apart.
Distortion	The unwanted change in waveform that occurs between points in a transmission system.
DOD	Department of Defense
DOE	Department of Energy
Downtime	The total time a system is out of service due to equipment failure.
DSN	Deep Space Network
Duplex Circuit	A circuit used for transmission in both directions at the same time. It can be called "full duplex" to distinguish it from "half duplex".

E	East
Earth Station	Ground-based equipment used to communicate with satellites.
ELV	Expendable Launch Vehicle
Encryption	The process of systematically encoding a bit stream before transmission so that an unauthorized party cannot decipher it.
EOIS	Earth Observing Information System
EOS	Earth Observing System
ESA	European Space Agency (Paris, France)
F	Fahrenheit
FDM	Frequency Division Multiplex
FLTSATCOM	Fleet Satellite Communications System
FM	Frequency Modulation
Frequency	An expression of how frequently a periodic (repetitious) wave form or signal regenerates itself at a given amplitude. The rate at which a current alternates, measured in Hertz, kilo-Hertz, megaHertz, etc.
Gbps	Gigabits per second
GHz	Gigahertz
GN	Ground Network
GOES	Geostationary Operational Environmental Satellite
GSFC	Goddard Space Flight Center
GSTDN	Ground Spaceflight Tracking and Data Network
Hardware	Physical equipment such as electronic, magnetic, and mechanical devices. Contrast with software.
Hertz (Hz)	A unit of frequency equal to one cycle per second.
HIRIS	High Resolution Imaging Spectrometer
H/W	Hardware
I/O	Input/Output

Intelsat	The International Telecommunications Satellite Consortium, formed in 1964 with the purpose of creating a worldwide communications satellite system.
IP	Internet Protocol
ISO	Information Systems Office (NASA)
"ISO"	International Standards Organization
JPL	Jet Propulsion Laboratory, Pasadena, CA
JSC	Johnson Space Center, Houston, TX
K	Kelvin
K	Thousand
Kbps, Kb/s	Kilobits per Second
KHz	KiloHertz
KSA	K-band single access (TDRSS service)
KSC	Kennedy Space Center, Cape Canaveral, FL
KW	Kilowatt
K-band	10.90 to 17.15 GHz
Line speed	Maximum data rate that can be reliably transmitted over a line.
M	Million
MA	Multiple access (TDRSS service)
Mbps, Mb/s	Megabits per Second
MHz	MegaHertz
MIPS	Million Instructions Per Second
Modem	A device that modulates and demodulates signals transmitted over voice-grade communications facilities.
Modulation	The process of varying some characteristics of the carrier wave in accordance with the instantaneous value or samples of the intelligence to be transmitted.
msec	Millisecond
MSFC	Marshall Space Flight Center, Huntsville, AL

MUX	Multiplexer
N	North
Nanosecond	One-billionth of a second.
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications Network
NASDA	National Space Development Agency (Japan)
NCAR	National Center for Atmospheric Research
NCC	Network Control Center
Network	A series of points connected by communications channels. An interconnection of computer systems and/or peripheral devices at dispersed locations that exchange data as necessary to perform the functions of the network.
NGT	Network Ground Terminal
NiCad	Nickel-Cadmium
NM	New Mexico
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NSSDC	National Space Sciences Data Center (NASA/GSFC)
OAST	Office of Aeronautics and Space technology (NASA)
OSI	Open Systems Interconnection
OSO	Office of Space Operations (NASA)
OSSA	Office of Space Science and Applications (NASA)
OSTDS	Office of Space Tracking and Data Systems (NASA)
Packet	A group of binary digits including data and call control signals which is switched as a composite whole. The data, call control signals, and error control information are arranged in a specified format.

Packet switching network	A network designed to carry data in the form of packets. The packet and its format is internal to that network. The external interfaces may handle data in different formats, and conversion is done by an interface computer.
PDS	Planetary Data System
PI	Principal Investigator
PLDS	Pilot Land Data System
PODS	Pilot Ocean Data System
Protocol	Strict procedure required to initiate & maintain communication. Protocols can exist at many levels in one network.
PSCN	Program Support Communications Network (NASA)
psi	Pounds Per Square Inch
PSS	Portable Simulation System
PSU	Physical Storage Unit
Real time	1) Pertaining to actual time during which a physical process transpires. 2) Pertaining to an application in which response to input is fast enough to effect subsequent input, as when conducting the dialogues that take place at terminal in interactive systems.
Redundancy	The presence of additional information or equipment. An example is a computer architecture in which duplicates of critical components are configured, one for normal operations and the other for back-up.
Ref.	Reference
Remote Access	Relating to the communication with a computer facility by a station that is distant from the computer.
REQ	Request
RF	Radio Frequency
RFP	Request for Proposal
ROM	Read-Only Memory
R&D	Research & Development
S	South

S-band	2000 to 2300 MHz
S/1700	1651 to 1999 MHz
SA	Single access (TDRSS service)
SAIS	Science and Applications Information System
SAR	Synthetic Aperture Radar
Sat, Satl	Satellite
SCI	Science
sec	Second
Signal	Aggregate waves propagated along a transmission channel and intended to act on a receiving unit.
Simulation	To represent and analyze properties or behavior of a physical or hypothetical system by the behavior of a system model. (This model is often manipulated by means of computer operations.)
SIRD	Support Instrumentation Requirements Document
SM	Statistical Multiplexer
SN	Space Network
SOCC	Satellite Operations Control Center
Software	A set of programs, documents, procedures, and routines associated with the operation of a computer system. Contrast with hardware.
SPAN	Space Physics Applications Network
SQ	Square
SSA	S-band single access (TDRSS service)
SSB	Space Science Board (NRC)
SSIS	Space Science Information System
STDN	Spaceflight Tracking and Data Network
Store and forward	Applied to communication systems in which messages are received at intermediate routing points and recorded (stored). They are then retransmitted to a further routing point or to the ultimate recipient.

STS	Space Transportation System
Supercomputer	Computer systems characterized by their very large size and very high processing speeds. Generally used for complex scientific applications.
S&F	Store and Forward
S/W	Software
TBD	To Be Determined
TCP/IP	Transport Control Protocol/Internet Protocol
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
TMIS	Technical Management Information System
TOPEX	Topography Experiment for Ocean Circulation
TP-4	Transport Protocol 4
T&E	Test and Evaluation
T/R	Transmit/Receive
Transponder	A receiver-transmitter combination that retransmits the received signal greatly amplified at a different frequency. Communications satellites usually contain several transponders.
TTY	Teletype
TV	Television
UHF	Ultrahigh Frequency (390 to 499 MHz)
USDA	U. S. Department of Agriculture
USGS	U. S. Geologic Survey
VHF	Very high frequency (30 to 300 MHz)
VHSIC	Very-High-Speed Integrated Circuit
W	Watt(s)
W	West
w/	with

w/o	without
WS	White Sands
WSGT	White Sands Ground Terminal, White Sands, NM
X-band	8000 to 10,999 MHz
X.25	A standard for packet switching procedures developed by CCITT.
ZOE	Zone of Exclusion